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Electric Power Stations

Testing and Operating

159 Illustrations

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EFFICIENCY TESTS
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ELECTRIC SUBSTATIONS
OPERATION OF ELECTRICAL MACHINERY

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PREFACE

The volumes of the International Library of Technology are made up of Instruction Papers, or Sections, comprising the various courses of instruction for students of the International Correspondence Schools. The original manuscripts are prepared by persons thoroughly qualified both technically and by experience to write with authority, and in many cases they are regularly employed elsewhere in practical work as experts. The manuscripts are then carefully edited to make them suitable for correspondence instruction. The Instruction Papers are written clearly and in the simplest language possible, so as to make them readily understood by all students. Necessary technical expressions are clearly explained when introduced.

The great majority of our students wish to prepare themselves for advancement in their vocations or to qualify for more congenial occupations. Usually they are employed and able to devote only a few hours a day to study. Therefore every effort must be made to give them practical and accurate information in clear and concise form and to make this information include all of the essentials but none of the non-essentials. To make the text clear, illustrations are used freely. These illustrations are especially made by our own Illustrating Department in order to adapt them fully to the requirements of the text.

In the table of contents that immediately follows are given the titles of the Sections included in this volume, and under each title are listed the main topics discussed.

International Textbook Company

B

CONTENTS

NOTE.—This volume is made up of a number of separate Sections, the page numbers of which usually begin with 1. To enable the reader to distinguish between the different Sections, each one is designated by a number preceded by a Section mark (§), which appears at the top of each page, opposite the page number. In this list of contents, the Section number is given following the title of the Section, and under each title appears a full synopsis of the subjects treated. This table of contents will enable the reader to find readily any topic covered.

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§ 56

OPERATION OF ELECTRICAL MACHINERY
(*Continued*)

OPERATION OF ELECTRICAL MACHINERY
(*Continued*)

EFFICIENCY TESTS

Serial 1151 — Edition 1

INTRODUCTION

COMPARISON OF METHODS

1. The commercial efficiency of a generator, or a motor, is the ratio of the output to the input, both being expressed in the same unit of power. An earlier method for determining this ratio was to run the machine under full-rated load conditions and to actually measure both the input and the output; by dividing the output by the input, the efficiency was at once determined. Some of the later methods of testing do not necessitate full-load operation. The machine in such a test is run as a motor without load, and the losses are determined by tests and by calculation.

The output of a machine must be equal to the input minus all the losses that occur; or, the output plus the losses equals the input. Knowing either the input or the output and the losses, the efficiency may be calculated. If the way that the losses vary with the output or the input is known, the efficiency throughout the range of load may be calculated.

2. The advantages of the running-light method over the earlier method, of which the Prony-brake test is an example, are: (1) The machine need not be run under full-load condition, as the losses can be determined from data taken at light load, and the full-load values calculated approximately. This saves power and does not require bulky apparatus for absorbing the load. (2) The results are more accurate. Since the

losses are small compared with the total input, a moderate percentage of error in the small measurements produces only little effect on the final efficiency; whereas, with the same percentage of error in the older method, in which total measurements are used, the efficiency is liable to an error at least as great as the errors of the readings.

A disadvantage is that in some machines the manner in which the losses in the machine under test vary with the load may not be definitely known. Generally, however, it is sufficiently accurate to assume that the machine meets the average conditions determined by numerous tests on the same general type of apparatus. This is especially true for direct-current apparatus.

LOSSES

3. The **losses** occurring in a generator or a motor come under the following headings:

1. Bearing friction and windage, together with brush friction on the commutator or on the slip rings. This may all be classed roughly as a friction loss, and, with constant speed, can be considered as independent of the load; that is, these losses may be assumed to remain constant at all loads. Where a machine is mounted on the shaft of a prime mover in such a manner that it cannot be separated therefrom, the frictional losses in bearings and in windage should be excluded from the efficiency calculations, owing to the practical impossibility of determining them satisfactorily.

2. I^2R loss in the armature, where I is the current in the armature and R the resistance of the armature. This loss changes greatly under different load conditions, but by means of tests and calculation may usually be definitely determined.

3. I^2R loss in the shunt-field and series-field windings, each being calculated separately. In a self-exciting machine, the losses in the field rheostat, the shunt winding, and the shunt to the series field are included in the field losses. For the shunt winding on a constant-potential machine, the loss does not vary greatly for different loads; in an overcompounded generator, the shunt-field loss increases somewhat as

the terminal voltage increases. The loss in the series winding varies for different load conditions, since the current through the series winding is changed.

4. I^2R loss in the brushes, and brush contact due to the current flowing against the resistance offered by the brushes and by their contact with the commutator. The resistance of carbon brushes decreases as the current heats the brush. It is difficult to state exactly the value of the brush resistance or the drop in volts caused by the current and brush resistance, since the composition of the brush, the current density, the brush temperature, the speed of rotation of the commutator, and the brush pressure are all factors in determining the values. In the case of carbon brushes worked at a density of from 30 to 40 amperes per square inch of contact surface, it is usually sufficiently accurate to allow a drop of about 2 volts for the complete set of brushes. The drop in volts multiplied by the armature current gives the approximate I^2R brush loss.

The relation between current density and drop in volts in the set of brushes may be expressed with approximate accuracy, when ordinary carbon brushes are used, by the following statements:

Up to 10 amperes per square inch, current density, the drop for every ampere per square inch is .125 volt.

Above 10 amperes per square inch, current density, the drop is 1.25 volts + .025 volt for every ampere per square inch above 10.

For 5 amperes per square inch, the drop is $.125 \times 5 = .625$ volt. For 40 amperes per square inch, the drop is $1.25 + (40 - 10) \times .025 = 1.25 + .75 = 2$ volts.

5. Molecular magnetic friction, or hysteresis, due to the constant reversals of magnetism in the armature core. This varies under different speed and voltage conditions, and should be determined with these conditions at normal value, since they do not usually vary in any simple proportion according to the speed or to the voltage.

6. Eddy-current losses in the armature core, in the pole faces, in wide conductors, and, in the case of cross-connected

armatures, the losses brought about, under certain conditions, by cross-currents from one portion of the windings to another portion. The eddy-current losses are usually small in direct-current machines, but are of more importance in alternating-current machines.

The sum of these losses corrected for full-load conditions gives the total loss at full load. The output divided by the output plus the losses, and the result multiplied by 100, or the input minus the losses divided by the input, and the result multiplied by 100, equals the efficiency expressed in per cent. By calculation and test the losses for a few different loads may be determined, and an efficiency curve constructed that will show very closely the efficiency at any load within the range of the machine.

DIRECT-CURRENT MACHINES

RESISTANCE MEASUREMENTS

4. Methods of Making Tests.—The resistance of field coils, the armature, and brushes vary under different load conditions; but, in the calculations, it is customary to use the constant values of resistance that the apparatus assumes during continuous operation at normal load. If convenient to load the machine, the resistance measurements may be made after a run that is sufficiently long for the machine to assume a constant temperature. This may be from 6 to 18 hours, according to the size and construction of the apparatus. In case the machine cannot be loaded conveniently, the cold resistances may be measured and then corrected for a normal value of temperature rise. This may have been stated in the machine specifications, but if not, approximately correct results may be obtained by assuming a rise of from 25° to 40° C. above room temperature. The standard room temperature is usually taken as 25° C.

The measurement of low resistances, such as those of armatures and series-field coils, requires special precautions,

since the values are very small. For this reason, the ordinary Wheatstone bridge is not suitable. A potentiometer, however, may be used satisfactorily if available.

The resistance measurement most frequently used is known as the "fall-of-potential method." The resistance to be measured and a known resistance of about the same value and of sufficient carrying capacity to transmit the current necessary for readable deflections without undue heating are connected in series in a circuit through which a steady current flows, preferably from a storage battery. By means of a low-reading voltmeter, the drops of potential are measured across the terminals of the unknown and the known resistance. The currents must have the same value when each measurement is made; therefore, it is well to insert an ammeter in the circuit in order to check current readings. If the currents are of the same value, the drops of potential are directly proportional to the resistances.

Let X = unknown resistance;
R = known resistance;
V' = voltmeter reading when connected across X;
V = voltmeter reading when connected across R.

Then,
$$X : R = V' : V$$
or,
$$X = \frac{V' R}{V}$$

If a known resistance is not available, the resistance of the field coils or of the armature may be determined by allowing current to flow through the part to be measured and then dividing the drop of potential across the terminals by the current flow through the device.

5. Precautions.—In measuring the resistance of armatures, the shunt-field circuit should be opened, and the voltmeter leads, consisting of flat copper strips, should be placed under adjacent brushes of opposite polarity in such a manner that firm contact with the commutator is secured. All of the brushes should be well fitted to the commutator. Further precautions are necessary, depending on the type of armature. If the armature is parallel wound, it will

probably have balancing rings or cross-connecting rings. The armature should be turned so that the brushes bear on commutator segments connecting as directly as possible to the balancing rings. Fig. 1 shows the proper position for the brushes; B_1+ and B_2+ are in contact with commutator segments connected to the same balancing ring, while B_1-

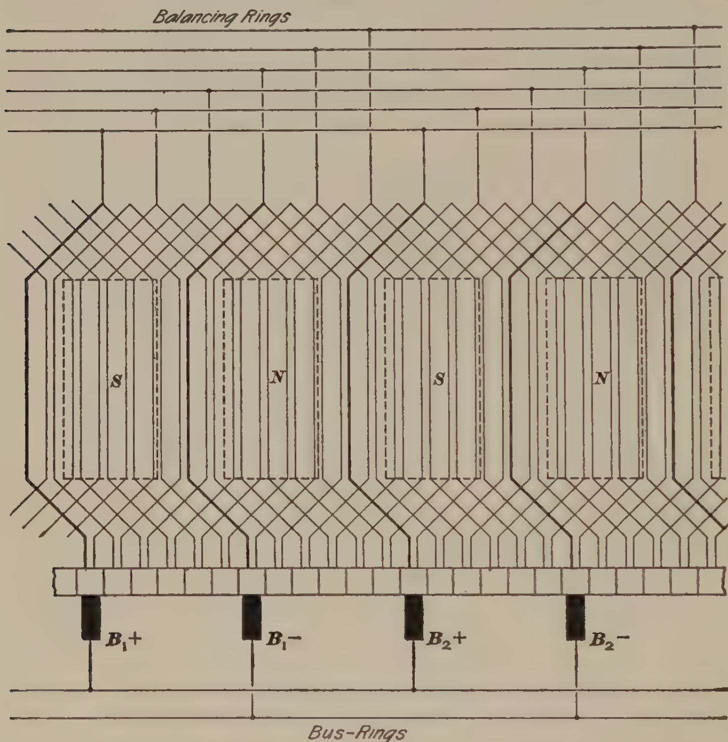


FIG. 1

and B_2- rest on other segments connected to another balancing ring. A reading of the voltmeter should be taken with the brushes in the position shown; then, the armature should be moved so that the brushes bear on segments connected to another pair of balancing rings, and a second reading taken. The mean of the two readings should be used. When the brushes are on segments that are cross-connected

by balancing rings, all the parallel circuits of the armature are connected in parallel, independently of the brushes; and, as the voltage drop is taken across the commutator, and not across the brushes, the effects resulting from unequal contact between brushes and commutator are eliminated.

In a series-wound armature or a parallel-wound armature without balancing rings, the precautions to be taken are to have the brushes well fitted and to connect the voltmeter leads directly to commutator segments situated the correct distance apart. This distance is equal to the total number of segments divided by the number of poles. In these armature measurements, the brush resistance is excluded, since the voltmeter terminals are placed on the commutator bars.

6. The brush resistance plus the armature resistance may be measured by connecting the voltmeter terminals to the bus-rings, shown in Fig. 1, care being taken that the brushes are placed so as to connect as directly as possible with the balancing rings. This measurement is subject to errors, since the resistance of the brushes and their contact resistance with the commutator differ for different current densities; also, if the brushes are not well fitted, the contact resistance may be far from normal.

It is usually better to measure the armature resistance alone, by placing the voltmeter terminals on the commutator bars, and then make allowance for the drop in voltage due to the current flowing through the brush resistance and the contact resistance.

7. When making the resistance measurements of the series-field coil (the series-field coil being in parallel with its adjusted series shunt), the voltmeter terminals should make contact directly with the terminals of the series coils. The coil terminals should be sandpapered, if necessary, in order to secure good contact with the voltmeter wires. The loss in the shunt-field windings may be determined by another method, as explained later.

8. Temperature Corrections.—The cold-resistance values of the armature and the series coil may be corrected

for full-load conditions. A temperature coefficient of .38 per cent. per degree centigrade for an initial room temperature of 25° C. may be assumed for the copper conductors. First, assume a rise of 25° C.; the increase in resistance is approximately $(.0038 \times 25)\ 100 = 9.5$ per cent. By increasing the cold resistance 9.5 per cent., or multiplying the cold resistance by 1.095, the hot resistance is determined. If an increase in temperature of 40° C. is assumed, the increase in resistance is $(.0038 \times 40)\ 100 = 15$ per cent. By increasing the cold resistance 15 per cent., or multiplying the cold resistance by 1.15, the hot resistance is determined.

The corrected resistance of a part of the machine multiplied by the square of the current passing through it gives the $I^2 R$ loss in that part.

RUNNING-LIGHT TEST

GENERATOR TEST

9. Preparations for Test.—In order to determine the combined friction, core, and eddy-current losses of a generator, the machine should be driven as a motor without load and the input measured. The machine, if new, should be run about an hour before taking readings, in order that the bearings may become thoroughly lubricated. The test may be made with the machine cold, and little error will be introduced. The speed must be the same as the rated generator speed in order to have the same windage and friction losses. The speed may be adjusted by the shunt-field rheostat. The field excitation should be as near as possible that required when the machine is a generator and is delivering its full load.

The electromotive force applied to the terminals when the generator is running as a motor should be higher than the normal terminal voltage when running as a generator. This is done in order that the counter electromotive force generated in the motor armature (which, when the motor is running light, is nearly the same as the electromotive force

impressed on the motor terminals) will be about the value of the total electromotive force generated in the generator armature. This total generated electromotive force at full load is equal to the generator-terminal electromotive force plus the drops in voltage, under full-load conditions, in the brushes, series-field coil, and armature.

The exact value of these drops may not be known, and the values may differ on different types of machines, but on some testing floors, a value of 3 volts for every 125 volts of the rating of the generator is allowed when testing for full-load efficiency. This means that if the rated voltage of the generator is 250 volts, the electromotive force applied to the motor terminals should be 256 volts.

10. Running as a motor in this way, the line supplies energy to overcome the bearing and brush friction, the windage, the core losses, and the eddy-current loss in the conductors. There is some I^2R loss in the armature during the test, due to the flow of the small armature current against the armature resistance. For extremely accurate work, this I^2R loss may be subtracted from the running-light loss. This I^2R loss, however, is usually so small that no appreciable error is made in the final result if it is neglected in the calculations; it should, however, be noted and allowance made for it if the loss in any case is found to be of sufficient importance.

11. Test Connections.—The connections for this test are shown in Fig. 2, where A is an ammeter connected in series with the armature of the machine to be run as a motor. Care should be taken that the ammeter is so connected as to measure only the armature current and not the armature and shunt-field current. B is a voltmeter for measuring the electromotive force applied to the armature terminals, and C is an ammeter connected to the shunt-field coil. The ammeters are protected by short-circuiting switches, which are opened only when a reading is to be made. D is the armature; F, the shunt field; SF, the series field, not used in this test; R, the shunt-field rheostat; S, the

main switch; *CB*, the circuit-breaker, and *WB* a water rheostat, or better, a metal rheostat, or a booster for adjusting the voltage applied to the armature terminals. A tachometer is used to measure the speed of the machine at any instant.

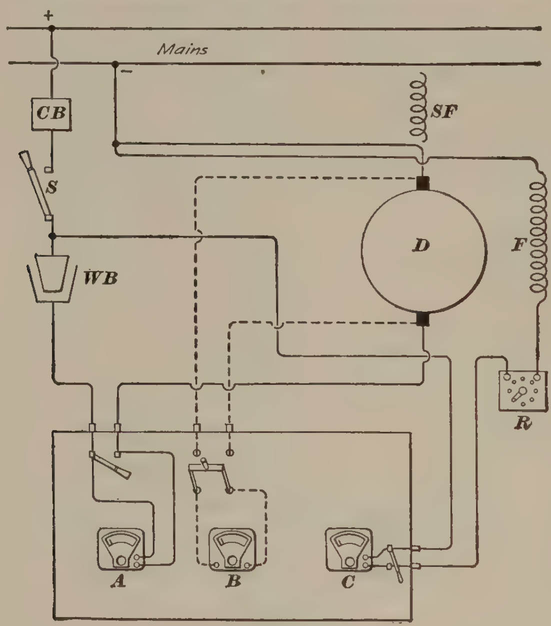


Fig. 2

It is necessary that the speed conditions should be known at the instant the other instruments are read; therefore, a tachometer is used instead of a revolution counter, which shows only the average speed for a given length of time.

12. Position of Brushes.—The motor is started by throwing in the circuit-breaker *CB* and closing switch *S*, *WB* being used as a starting rheostat. The brushes should be set at the no-load neutral position. This position may be determined as follows: While the motor is running, voltmeter points, connected to a voltmeter *V*, Fig. 3, reading about 15 volts, are held on the commutator surface a distance apart equal to the space between the centers of two

adjacent commutator bars. These points are moved back and forth over the circumference of the commutator until a position is reached where the voltmeter either reads zero or gives the minimum reading. This is the *no-load neutral position*, and the brushes are set accordingly.

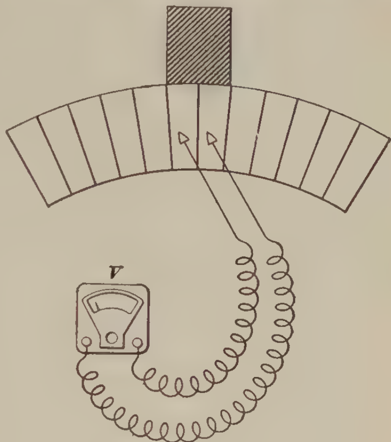


Fig. 3

13. Conduct of Test. The resistance in the rheostat *WB*, Fig. 2, should now be adjusted, either by changing the distance between the plates or by adding a little more salt to the water, until the counter electromotive force is of correct value. In this case, the counter electromotive force is practically the same as the applied electromotive force.

The speed is brought up to its rated value by adjusting the field rheostat. The man that takes the tachometer reading adjusts the speed. When the speed and the voltage are correct, the two ammeters, the voltmeter, and the tachometer are read as near as possible at the same time. It will be found that the readings of ammeter *A* will vary somewhat, but if care is taken to read it only after the speed has been correct for at least 10 seconds, the ammeter needle will be steady and the values will not vary greatly. Five sets of readings should be taken at each load point, and the average of these readings should be used.

14. Test-Sheet Data.—The readings should be recorded on a prepared **test sheet** similar to that shown in Fig. 4. The resistance measurements of the armature and the series field in parallel with its shunt should be recorded first. It is assumed that the cold-resistance values are obtained and then the hot resistances calculated. The values recorded on

TEST SHEET

Date ________

D.-C. MOTOR OR GENERATOR

Tested by ________

Rating, *500 K. W.* *Volts*, *575.* *Amperes*, *870.* *Speed*, *400 R. P. M.*
Machine No. 1. *Dimension of Brushes*, 1 *in.* × $1\frac{1}{4}$ *in.* *Number of Studs*, *8.*
Number of Brushes per Stud, *8.* *Current Density*, *22 Amps.*

RESISTANCE MEASUREMENTS

Armature				Series Field and Series-Field Shunt			
Volts	Amps.	Res., Cold	Res., Hot Calculated	Volts	Amps.	Res., Cold	Res., Hot Calculated
.0435	6	.00725	.00794	.0388	20	.00194	.002045

RUNNING LIGHT

Volts	Amps. of Arm.	Watts	Amps. Shunt	Speed
525	28.7	15,068	5.76	400
540	29.2	15,768		400
556	29.7	16,513		400
571	30.4	17,358		400
586	30.9	18,107		400
601	31.7	19,052		400

EFFICIENCY AND LOSSES

Per-Cent. Load	0	25	50	75	100	125
Terminal volts as generator	525	537.5	550	562.5	575	587.5
Amps., line	0	232.5	455	666	870	1,064
Amps., shunt field .	5.76	5.9	6.03	6.17	6.31	6.5
Amps., arm.	5.76	238.4	461	672.2	876.3	1,071
Amps., series field and series-field shunt	5.76	238.4	461	672.2	876.3	1,071
IR drop	0	2.9	5.6	8.2	10.7	13.2
Volts as motor, running light	525	540	556	571	586	601
Friction and core losses	15,068	15,768	16,513	17,358	18,107	19,052
I^2R arm. loss . . .	0	451	1,687	3,588	6,097	9,107
I^2R shunt-field and rheo. loss	3,024	3,171	3,316	3,471	3,628	3,819
I^2R series field and series-field shunt loss	0	116	435	924	1,570	2,345
I^2R brush loss . . .	0	119	461	1,008	1,753	2,678
Total	18,092	19,625	22,412	26,349	31,155	37,001
K. W. output . . .	0	125	250	375	500	625
K. W. input	18.1	144.63	272.41	401.35	531.16	662
Per-cent. efficiency .	0	86.43	91.77	93.43	94.13	94.41

FIG. 4

the sheet shown in Fig. 4 were based on actual measurements. The temperature rise of the armature was about 25° C. The temperature rise corresponding to the increase in resistance of the combined series field and series-field shunt is about 14° C. The temperature rise of the series field alone is somewhat more than this, since the series-field shunt changes in resistance but little with increased temperature.

The resistance measurements may be made either by the aid of a low-reading ammeter and a millivoltmeter or by comparing the drops across the known and the unknown resistances, as previously described. Enough current should be allowed to flow through the resistance, so that a readable deflection on the millivoltmeter connected across the terminals of the resistance can be obtained. A rheostat may be used to control the current.

15. The running-light readings are now taken. The machine is run as a motor, and the voltage applied to the armature terminals is adjusted so that the counter electromotive force is 525 volts, which, in this case, is the rated no-load voltage. The speed is adjusted to the correct rated value, and readings are taken on the instruments A, B, and C, Fig. 2. The product of the volts and the armature amperes equals the sum of the bearing friction, brush friction, windage, hysteresis, and eddy-current losses at no load. The I^2R armature loss is usually negligible at no load.

As just stated, the rated no-load voltage of the machine under consideration is 525, and the full-load voltage, 575. The rise in voltage is 50. At 25-per-cent. load, the generator terminal voltage is $525 + \frac{50}{4} = 537.5$; at 50-per-cent. load, $525 + \frac{50}{2} = 550$; at 75-per-cent. load, $525 + \dfrac{50 \times 3}{4} = 562.5$; at 100-per-cent. load, $525 + 50 = 575$; and 125-per-cent load, $525 + \dfrac{50 \times 5}{4} = 587.5$. The corresponding outputs are 125, 250, 375, 500, and 625 kilowatts.

At these loads, the current that flows through the line when the machine is operating as a generator is found by dividing the watts output by the terminal voltage.

A long shunt connection is used in this machine, so that the current for the shunt field flows through both the armature and the series-field circuit. The shunt-field current may be assumed to increase in proportion to the increase in terminal electromotive force. The overcompounding is accomplished by the series coils. At no load, the shunt-field current is 5.76 amperes, as found by ammeter *C*, Fig. 2; at 25-per-cent. load, the current is $5.76 \times \frac{537.5}{525} = 5.9$ amperes; at 50-per-cent. load, the current is $5.76 \times \frac{550}{525} = 6.03$ amperes, etc. The values of the shunt current should be recorded in Fig. 4; and to obtain the armature and series-field current, the shunt current should be added to the line current.

16. The values of terminal voltages as a generator, and the amperes in the line, in the series field and its shunt, and in the armature are recorded as shown. The IR drops in the armature, series-field circuit, and brushes, at the different load points, are found by multiplying the armature current by the hot resistance of the armature plus the hot resistance of the combined series field and its shunt, and adding to this the drop in volts caused by the brushes and brush-contact resistance. The hot resistance of the armature and series-field circuit is $.00794 + .002045 = .009985$ ohm.

The current density in the brushes at full load is $\frac{876.3}{1 \times 1.25 \times 8 \times 4} = 22$ amperes per square inch. For this rather low density, the brush drop might be somewhat under 2 volts, but the approximate value of 2 volts will be used in the calculations for full-load conditions and for the set of brushes (four positive and four negative groups). Brush-resistance data is rather difficult to determine with great accuracy. An approximate value based on experimental carbon-brush data is close enough for ordinary purposes, since a slight inaccuracy makes little difference in the calculated machine efficiency. For a load of 25 per cent., allow $2 \times \frac{1}{4} = .5$ volt; for 50 per cent., $2 \times \frac{1}{2} = 1$ volt; for 75 per

cent., $2 \times \frac{3}{4} = 1.5$ volts; for 100 per cent., 2 volts; for 125 per cent., $2 \times \frac{5}{4} = 2.5$ volts.

The whole IR drop at a load of 25 per cent. equals $238.4 \times .009985 + .5 = 2.9$ volts; at 50 per cent., $461 \times .009985 + 1 = 5.6$ volts; at 75 per cent., $672.2 \times .009985 + 1.5 = 8.2$ volts; at 100 per cent., $876.3 \times .009985 + 2 = 10.7$ volts; at 125 per cent., $1{,}071 \times .009985 + 2.5 = 13.2$ volts. Record these values of drops in voltage and add them to the corresponding values of generator-terminal voltage in order to obtain the running-light motor volts.

17. Make a running-light test for each of these values of motor volts, in order to obtain the friction and core losses corresponding to the different load points. The friction losses change only slightly for the different loads so long as the speed is constant, but the core losses increase with increasing load, due to the greater density of the lines of force brought about by the higher excitation.

Record the motor volts, the armature amperes, and the watts (product of motor volts and armature amperes) obtained from the running-light readings. Also record the watts under the side heading friction and core losses.

18. The I^2R armature loss is found by multiplying the square of the armature current by the hot resistance of the armature. At full load, $876.3^2 \times .00794 = 6{,}097$ watts.

The I^2R loss in the shunt field and rheostat is found by multiplying the calculated shunt-field current by the generator-terminal volts. With the exception of the first value, 5.76 amperes, the values of the shunt current obtained from the running-light test are not used in determining the I^2R loss in the shunt field. This is due to the fact that the generator values of shunt-field current would not be the same as the motor-test values because of the absence of the series field during the test. At full load, $6.31 \times 575 = 3{,}628$ watts.

I^2R series field and series-field shunt loss equals the product of the square of the current flowing through the series-field circuit and the hot resistance of the combined

series coil and its shunt. At full load, $876.3^2 \times .002045$ = 1,570 watts.

The I^2R brush loss is determined by multiplying the armature current at any load point by the drop in volts allowed for the brushes at that point. At 25-per-cent. load, $238.4 \times .5 = 119$ watts; at 50-per-cent. load, $461 \times 1 = 461$ watts; at 75-per-cent. load, 672.2×1.5 1,008 watts; at 100-per-cent. load, $876.3 \times 2 = 1,753$ watts; **at 125-per-cent. load, 1,071** $\times 2.5 = 2,678$ watts.

19. The losses are recorded on the test sheet, and the sum of the losses is computed for each load point. The total loss added to the output, both expressed in kilowatts, equals the kilowatt input. The commercial efficiency of the machine, expressed in per cent., equals the output divided by the input and the quotient multiplied by 100.

20. Efficiency Curve.—An **efficiency curve** may be plotted similar to the one shown in **Fig.** 5. The values of

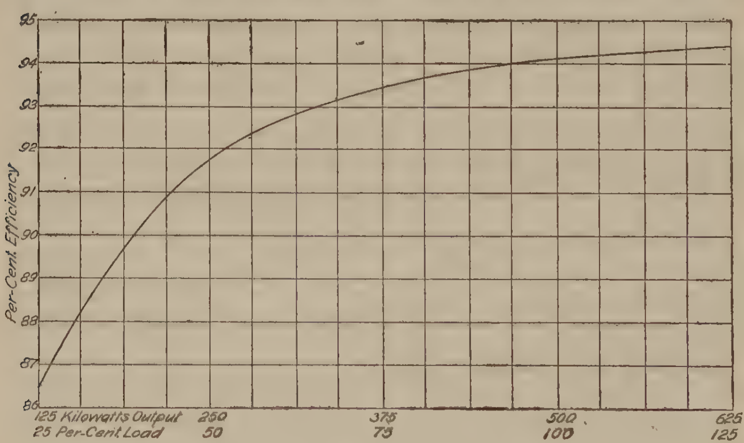


FIG. 5

the efficiencies are laid off as ordinates, and the load points, or kilowatts output, are laid off as abscissas. The data for this curve is taken from the test sheet. The test sheet and curve should be filed for future reference.

MOTOR TEST

21. A shunt or a compound motor may be tested in a manner similar to that just described for a generator, provided the test is slightly modified to suit the altered conditions. The connections shown in Fig. 2 and a test sheet similar to that shown in Fig. 4 may be used. In the case of a compound motor, the series field should be disconnected during the running-light test.

The losses are similar to those in a generator; namely, friction and core losses L_{fc}; armature loss $I_a^2 R_a$, armature current squared times the hot armature resistance; series-field loss $I_a^2 R_{se}$, armature current squared times the hot series-coil resistance; brush loss $I_a^2 R_b$, or $I_a V_b$, armature current squared times the brush resistance, or armature current times volts drop in brushes; shunt-field loss $I_s^2 R_s$, or $I_s E$, hot shunt-field current squared times the hot shunt-coil resistance, or shunt-field current times the line voltage.

The input at full load $I_m E$ equals the motor current, usually marked on the name plate of the machine, multiplied by the line voltage. The motor current equals the sum of the armature current and the hot shunt-field current. The output W_o, expressed in watts, at full load equals the rated horsepower of the motor, usually stated on the name plate, multiplied by 746.

The input equals the output plus the losses; the relation of the values may be expressed as follows:

$$I_m E = W_o + L_{fc} + I_a^2 R_a + I_a^2 R_{se} + I_a V_b + I_s E$$

22. The cold resistances of the armature, series coil, and shunt coil should be measured and corrected for a normal temperature rise. Multiplying the cold resistances by 1.18 will give approximately correct results. The current I_s of the hot shunt field equals the line voltage divided by the hot resistance of the shunt field. If the motor current I_m for full load is known, subtract from it the shunt current in order to obtain the armature current I_a

The drop in volts in the armature and series field equals $I_a R_a + I_a R_{se}$. To this add an allowance of from 2 to 2.5 volts

for brush drop $I_a R_b$. The total drop is $I_a R_a + I_a R_{se} + I_a R_b$. When making the running-light test to determine the friction and core losses at full load, the electromotive force applied to the armature terminals should be adjusted by rheostat WB, Fig. 2, so as to be equal to the counter electromotive force of the armature at full load. This counter electromotive force equals the line voltage minus the total drop. The motor speed should be adjusted by field rheostat R, Fig. 2, so as to be as near the normal full-load speed as possible. The brushes should be placed at the neutral position.

23. The L_{fc} loss equals the electromotive force applied to the armature terminals multiplied by the current flowing through the armature during the running-light test. The $I_a^2 R_a + I_a^2 R_{se} + I_a V_b$ loss equals the total drop multiplied by the full-load armature current, or $I_a (V_a + V_{se} + V_b)$. The output W_o is known, and the $I_s E$ loss can be calculated. If the current marked on the name plate is correct, the output plus the calculated losses will equal the input. If the full-load current is not known, a trial value of current may be assumed, a running-light test made, and the other losses calculated. If the assumed current satisfies the relation between output, losses, and input, as expressed by the formula of Art. **21**, it is correct; if not, another trial value is taken. The efficiency equals the watts output divided by the watts output plus the watts lost.

24. If the counter electromotive force of the motor changes only slightly during the range of load, the L_{fc} loss can be considered constant; the $I_s E$ loss may also be considered constant. These two losses may be called *constant losses*. Since the armature current changes at different loads, the $I_a^2 R_a$, the $I_a^2 R_{se}$, and the $I_a V_b$ losses will change; these may be called *variable losses*. As these losses change nearly in proportion to the square of the armature current, little error is introduced in the final result if the variable loss for 25-per-cent., or $\frac{1}{4}$, load is taken as $\frac{1}{16}$ of the full-load variable loss, the current being approximately $\frac{1}{4}$ and the losses $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$; for 50-per-cent. load, $\frac{4}{16}$, or $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$; for

75-per-cent. load, $\frac{9}{16}$, or $\frac{3}{4} \times \frac{3}{4} = \frac{9}{16}$; for 125-per-cent. load, $\frac{25}{16}$, or $\frac{5}{4} \times \frac{5}{4} = \frac{25}{16}$. Adding the constant and variable losses for the different load points produces the total losses at these points, and the corresponding efficiencies may be calculated.

If greater accuracy is desired for the partial-load points, an efficiency may be assumed for a load point, and the motor current calculated by multiplying the horsepower at that point by 746, and dividing by the product of the assumed efficiency (expressed as a decimal) and the line voltage. The losses are then calculated. If the calculated input equals the output plus the calculated losses, the assumed efficiency is correct; if not, another assumption may be made and tested. At the low-load points, the current will be somewhat more than one-fourth or one-half the full-load value, due to the lower efficiencies.

LOADING-BACK TEST

25. Preparations for Test.—Where two direct-current generators, or motors, of the same type and capacity are available, the Hopkinson, or **loading-back,** method of testing may be employed. Both machines, one acting as a motor and the other as a generator, are made to carry full load, and all the losses are measured under these conditions.

The two machines are belted together, or have their shafts coupled, so that the one that acts as the motor may mechanically drive the one that acts as the generator. Most of the current necessary to drive the motor is delivered by the generator armature, but enough current is taken from a power circuit to make up for the losses in the motor and generator.

26. Test Connections.—The connections for a loading-back test are shown in Fig. 6, where WB is the water-rheostat, or other regulating device, for adjusting the voltage of the supply circuit; $S\ WB$, a starting water-rheostat box provided with a short-circuiting switch; A_l, the line ammeter; G, the generator, and A_g its armature ammeter; M, the motor, and A_m its armature ammeter; F_g, the generator shunt-field ammeter;

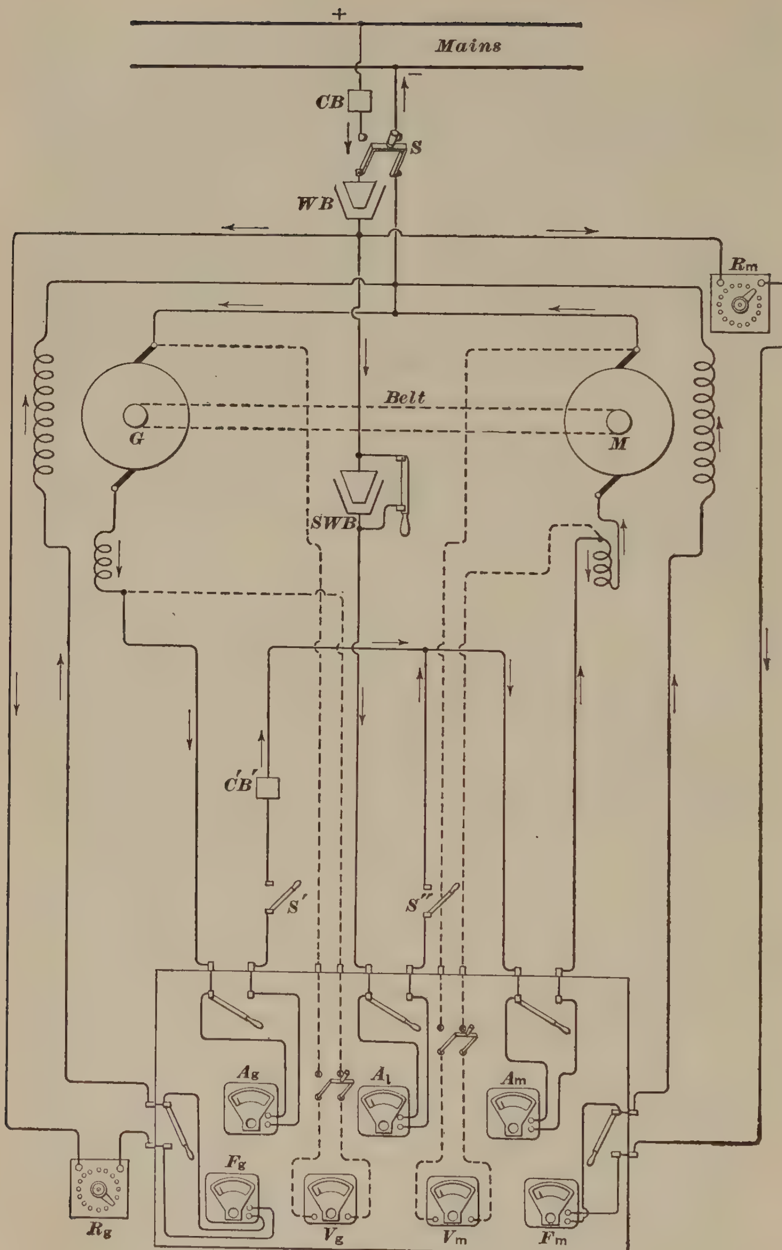


FIG 6

F_m, the motor shunt-field ammeter; V_g, the voltmeter for the generator terminals; V_m, the voltmeter for the motor terminals; R_g, the generator field rheostat; R_m, the motor field rheostat; CB and $C'B'$, circuit-breakers; and S, S', and S'' switches for the power circuit, generator, and motor. Short-circuiting switches are provided for the ammeters. The series-field coil connections of the motor are the reverse of those of the generator, so as to make an accumulatively wound motor.

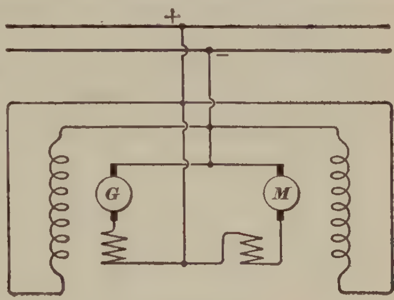


FIG. 7

Fig. 7 shows a simplified diagram of the connections for the test. The two machines are connected in parallel, and the generator and the supply circuit furnish current to the motor.

27. Conduct of Test.—The brushes of the motor and generator should be moved to their running positions. The motor is started by closing circuit-breaker CB and switches S and S'', Fig. 6, and using rheostat SWB as a starting resistance. When the motor is up to speed, the resistance of rheostat SWB is entirely cut out by the short-circuiting switch.

The electromotive force of generator G, indicated by V_g, is built up until it is equal and opposite to the supply voltage, as indicated by V_m. When in this condition, a voltmeter connected across the open switch S' will read zero volts; the voltage of G should then be increased a trifle, so that the voltmeter needle inclines slightly backwards, provided it had a positive reading before the voltage of G was brought up to that of the supply circuit. Circuit-breaker $C'B'$ and switch S' are then closed. The generator G will furnish only little, if any, current until its voltage is further raised. This is done by cutting out some of the resistance in the generator field rheostat, thus raising the generator voltage

slightly above that of the supply mains. Current will now flow from G through M. Both generator G and motor M begin to take on load. Generator G alone cannot supply enough current to motor M to enable the motor to drive G mechanically, because more electric power is required to drive M than M can mechanically supply to G, and G cannot transform all of the mechanical power it receives into electric power for M. Hence, the amount of loss in each machine must be compensated by electric power from the supply mains.

28. The load on the machines is increased to full-load conditions by cutting out resistance in the generator field rheostat R_g and by speeding up the motor by cutting in resistance in the motor field rheostat. Adjusting rheostat WB also varies the current output of the armature G, since the current depends, among other conditions, on the difference between the voltage of G and that of the supply circuit. The voltage of G must be held at its normal value.

Great care must be exercised when loading the machines, as a small change in the strength of the field of either machine will materially alter the current flowing. This is due to the low resistance of the circuit through the two armatures. The ammeters A_g and A_m will show the increase in current as the load is built up. The current through the ammeter A_l will increase but slowly. The load should be built up until ammeter A_g shows that the generator is furnishing its full-load current.

The speed should be maintained at normal value. An operator tests the speed with a tachometer and adjusts the motor field rheostat R_m as found necessary. Adjustments should be made with care, while the readings of the instruments should be frequently noted. No sudden changes in any of the conditions should be allowed, because of the danger of throwing the various magnetic and electric values involved out of balance, and thus causing excessive current flow.

29. The set should be run under full-load conditions long enough for the temperature of the generator to become

constant and to properly bed the brushes on the commutator. The time required varies for different machines and for different conditions of testing; it may be from 6 to 18 hours.

When current and voltage conditions for full load are constant and the generator has attained approximately full-load temperature, as checked by a thermometer, the readings for efficiency may be made. Readings are taken on instruments F_g, F_m, A_m, A_l, V_g, A_g, Fig. 6, when the voltmeter V_g, the ammeter A_g, and the tachometer show simultaneously that the generator voltage, the current, and the speed are correct. The average of five readings should be used and recorded.

30. Test-Sheet Data.—A form of test sheet similar to the one shown in Fig. 8 may be used. The output of the generator is equal to the product of the readings of instruments A_g and V_g, Fig. 6, or $I_{ga} \times V$. The power supplied to the motor armature is the product of the reading of the voltmeter V_g and the sum of the readings of ammeters A_g and A_l, which is totaled by the reading of ammeter A_m. The product may be expressed either as $(I_{ga} + I_l)\ V$ or as $I_m \times V$. By adding to this the shunt-field losses in both machines, or $(I_{gf} + I_{mf})\ V$, the result is the total input required to compensate for the bearing friction, windage, core losses, and $I^2 R$ losses of both machines and to provide the actually measured generator output $I_{ga} \times V$. The connecting wires should be of such size that there is little drop of potential due to current flowing through them, therefore, the readings of V_g and V_m are practically alike.

The joint efficiency is equal to

$$\frac{\text{output}}{\text{input}} = \frac{I_{ga} \times V}{(I_m + I_{gf} + I_{mf})\ V} = \frac{I_{ga}}{I_m + I_{gf} + I_{mf}}$$

The efficiency of each machine is equal to $\sqrt{\dfrac{I_{ga}}{I_m + I_{gf} + I_{mf}}}$.

With the values indicated on the test sheet, the efficiency of each generator is 94.7 per cent.

31. If efficiencies at partial-load points are desired, the generator-armature current I_{ga} and the generator voltage V are adjusted to the proper values for the selected load point,

TEST SHEET

TWO DYNAMOS, NOS. 1 AND 2

Date____________

Tested by____________

Normal Output, 500 K. W. *Volts, 550.* *Amperes, 910.* *Speed, 514.*

Per-Cent. Load	Revolutions per Minute	Generator Field Current $= I_{gf}$	Motor Field Current $= I_{mf}$	Generator-Armature Current $= I_{ga}$	Generator Volts $= V$	Generator Output $= I_{ga} \times V$	Line Current $= I_l$	Motor-Armature Current $= I_m = I_{ga} + I_l$	Total Input to Machines $= (I_m + I_{gf} + I_{mf}) V$	Joint Efficiency $= \frac{I_{ga}}{I_m + I_{gf} + I_{mf}}$	Single-Machine Efficiency $= \sqrt{\frac{I_{ga}}{I_m + I_{gf} + I_{mf}}}$
25											
50											
75											
100	514	4.68	4	910	550	500,000	95	1,005	557,524	89.77	94.7
125											

FIG. 8

and a set of readings taken. The speed should be kept approximately constant during the tests on the different load points. To shut down the test, open circuit-breakers CB, $C'B'$, and switches S, S', S'', Fig. 6; then cut in the resistance of rheostat SWB, in case the set is to be started again.

SERIES-MOTOR TEST

32. Preparations for Test.—The test connections for determining the efficiency of a direct-current, series-wound motor, where two similar motors are available, are shown in Fig. 9. The shafts are coupled together so that the motor and generator armatures may rotate in unison. A simple method of securing this result is to slip an iron sleeve over both pinions. Setscrews on the sleeve are forced down between the teeth of the pinions. The starting water rheostat SWB, the circuit-breaker CB, the motor armature M_a, the motor field M_f, and the field of the motor that is to act as a generator G_f are connected in series between the trolley and the ground. The generator armature G_a is connected to a water rheostat GWB for the purpose of absorbing the load.

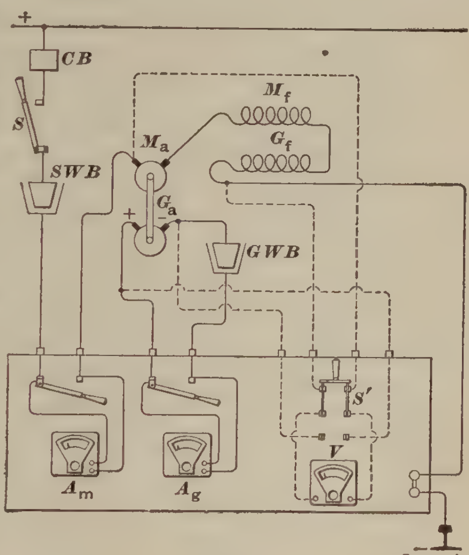


FIG. 9

33. Conduct of Test.—Start the motor by closing circuit-breaker CB and switch S, and operating rheostat SWB. The generator is separately excited, and current will flow through the generator rheostat GWB as soon as

Date_______

Tested by_______

TEST SHEET

TWO SERIES MOTORS, NOS. 1 AND 2

Rated Output, 125 H. P. *Rated Voltage, 500.* *Rated Full-Load Current, 208 Amperes.*

Motor Input Current	Voltage Motor Plus Generator Field	Total Input	Generator-Armature Output Current	Generator-Armature Voltage	Total Output	Joint Efficiency Motor-Generator Set	Efficiency Single Motor
208	525	109,200	192	460	88,320	81	90

FIG. 10

armature G_a starts to rotate. Adjust rheostat GWB until the motor ammeter A_m shows the proper rated full-load current for the motor. If the rated full-load current is not known, it can be approximately determined by multiplying the value of the rated horsepower by 746, and then dividing by the product of the rated voltage and an assumed efficiency, expressed as a decimal, of from 80 per cent. for small motors to 90 per cent. for large motors, or approximate input current equals rated horsepower × 746 ÷ assumed efficiency × rated voltage.

The voltage across the motor armature and its field coil should be approximately the rated voltage (usually 500 volts) when the rated full-load current is flowing through the motor armature, its field, and the generator field. The voltage across the motor armature and its field coil may be measured by temporarily connecting the voltmeter to the motor terminals (excluding the generator field).

34. The motor should be run under full-load conditions until the windings have assumed approximately normal temperature and the brushes have worn into good contact with the

commutator. Readings should then be taken of instruments A_m and V, with the switch S' in its upper position, and of A_g and V, with S' in its lower position. The readings should be taken as near the same time as possible, to avoid inaccuracies due to changes in the line voltage and load conditions. If two voltmeters are available, one may be used for the motor circuit and the other for the generator circuit, and all the readings taken at a given signal.

The product of the readings of instruments A_m and V (S' in upper position) is the total watts input to the motor-generator set. The product of the readings of instruments A_g and V (S' in lower position) is the total output of the set. The joint efficiency of the set is equal to $\frac{\text{total output}}{\text{total input}}$.

The efficiency of each machine is approximately the square root of the efficiency of the set, or $\sqrt{\frac{\text{total output}}{\text{total input}}}$. Since the motor and generator in this test are not working under exactly the same load conditions, the efficiency for each machine thus found may be slightly inaccurate; since, however, the efficiency of the motor changes but little for slight changes in load conditions, the results should be practically correct. The input current may be adjusted for partial loads, and the efficiency determined at these points. In Fig. 10 is shown a form of test sheet that may be used for this test.

ALTERNATING-CURRENT MACHINES

ALTERNATOR RUNNING-LIGHT TEST

35. Preparation for Test.—The losses in the armature and field of an alternator are of the same character as those in a direct-current machine; namely, friction losses, iron losses, and copper, or I^2R, losses for armature and field. The hysteresis and eddy-current losses are practically constant at all loads, while the copper losses increase as the square of the current and become large at overloads.

The simplest method of making an efficiency test on an alternator is to run it as a synchronous motor under no-load conditions, in order to determine the core and friction losses; then calculate the full-load copper losses for armature and field, thus obtaining the total losses, and, finally, calculate the efficiency from the relation between output and input.

36. Test Connections.—The connections for the running-light test are shown in Fig. 11. The three-phase alternator armature is shown at A, and its separately excited field at F. This is the conventional method of representing an alternator; revolving-field machines are now quite generally used. CB are circuit-breakers; S is the main switch connecting to the three-phase mains, and S' is the field switch connecting to the DC mains. To this latter switch, when opened, is connected a small resistance to take up the discharge of the field when the switch is thrown out. R is the field regulating rheostat; A_{fa}, the field ammeter; A_{fv}, the field voltmeter; A_a, an ammeter for measuring the current in one phase; W, an indicating wattmeter; PT, a potential transformer, used in case of high voltage; and ST, a series transformer, used in case of a large main current and also to prevent having high-tension wires on the testing table.

37. Conduct of Test.—The machine is started, synchronized, and thrown into connection with the *A C* mains, having the proper frequency and voltage. The field current is then adjusted until the armature current taken from the *A C* mains is of minimum value. The power factor under these conditions is nearly unity. The power expended on the

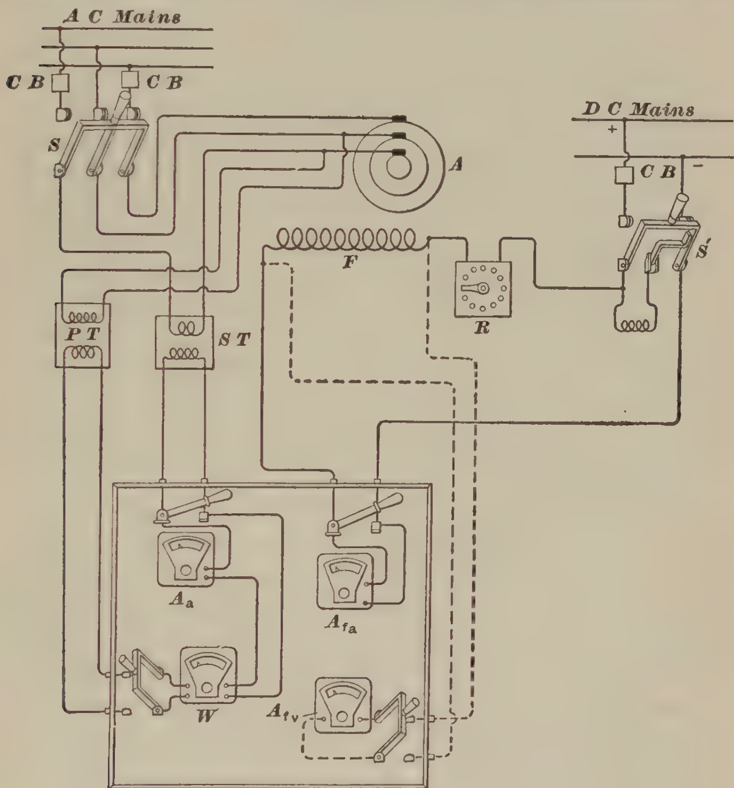


FIG. 11

armature is found by multiplying the indicating wattmeter reading by 2, since the load is a balanced one and the power factor is practically unity. It is presumed that the voltage of each phase is the same. This power represents the losses due to friction, hysteresis, and eddy currents, and these losses may, with little error, be considered as constant at all loads.

38. Copper Losses.—The copper loss for the separately excited field is equal to the product of the field current at full load and the voltage, under normal temperature conditions, across the terminals of the field coil, or to the current squared and multiplied by the hot resistance of the field. The reading of ammeter A_{fa} multiplied by the reading of voltmeter A_{fv} equals the copper loss in the separately excited field. The loss in the separately excited field rheostat is not charged to the machine. Owing to the demagnetizing effect of the armature current at full load, the full-load field current will be somewhat more than the field current obtained during the running-light test, but the effect of this increase on the efficiency calculations is practically negligible. If the machine can be run as a generator on full load, the field current may be measured, and this value can be used for determining the field copper loss. After the machine has attained its normal running temperature, the resistance of the field coils and the resistance between two armature slip rings, or terminals, of the same phase should be measured. If the resistances are measured when the machine is cold, they should be corrected for a temperature rise of about 40° C.

39. The full-load copper loss in the armature of a polyphase machine equals the product of one-half the hot resistance (or corrected cold resistance) from terminal to terminal and the square of the equivalent full-load current that would flow in a single-phase system. For a balanced two-phase circuit, the equivalent current is twice the current in any one of the four line wires. For a balanced three-phase circuit, the equivalent current is $\sqrt{3}$ times the current in any one line wire. The resistance of the three-phase armature should be measured between any two of the three terminals when the machine is hot, or the cold resistance should be measured and corrected for temperature rise. To obtain the armature copper loss of a three-phase machine, multiply the square of $\sqrt{3}$ times the rated full-load line current by one-half the hot resistance between any two terminals.

40. The total loss is the sum of the friction, hysteresis, eddy-current, I^2R field, and I^2R armature losses. The data may be tabulated on a test sheet of the general form shown in Fig. 4, but the sheet should be changed slightly to suit the altered conditions.

$$\text{Efficiency} = \frac{\text{rated output}}{\text{rated output} + \text{total loss}}$$

SYNCHRONOUS-MOTOR RUNNING-LIGHT TEST

41. The efficiency of a synchronous motor may be determined in a manner similar to that of the preceding test. The rated full-load armature current, which is usually stamped on the name plate of the machine, may be used when calculating the I^2R armature loss. The approximate value of field current is determined from the running-light test.

ALTERNATOR TEST WITH AUXILIARY MOTOR

42. Preparations for Test.—The following test requires that the alternator should be driven by a motor that is between 15 and 20 per cent. of the size of the alternator. To avoid a large amount of armature reaction in the driving motor, the motor-armature current should never be much greater than one-half of its normal full-load current. An exciter generator may be employed as a motor for this test. The direct current for the alternator field coils is obtained from another exciter or from a direct-current lighting or power line.

The motor pulley is belted to the generator pulley, and the size of the pulleys is so proportioned that the generator will run at its rated speed. It is advisable to use either a glued belt or one with a light lacing on the splice in order to prevent the ammeter needle from jumping when the splice passes over the pulleys. Belt tension should not be excessive.

In order to reduce armature reaction, the motor brushes should be set as near the no-load neutral position as possible

and still have sparkless commutation. The commutator should be run dry.

43. Test Connections and Test Sheet.—The driving motor and alternator connections are shown in Fig. 12. In addition to the alternator instruments shown in Fig. 11, voltmeter A_v, Fig. 12, is used. The wattmeter W, Fig. 11, may be omitted. In Fig. 12, the motor-armature ammeter

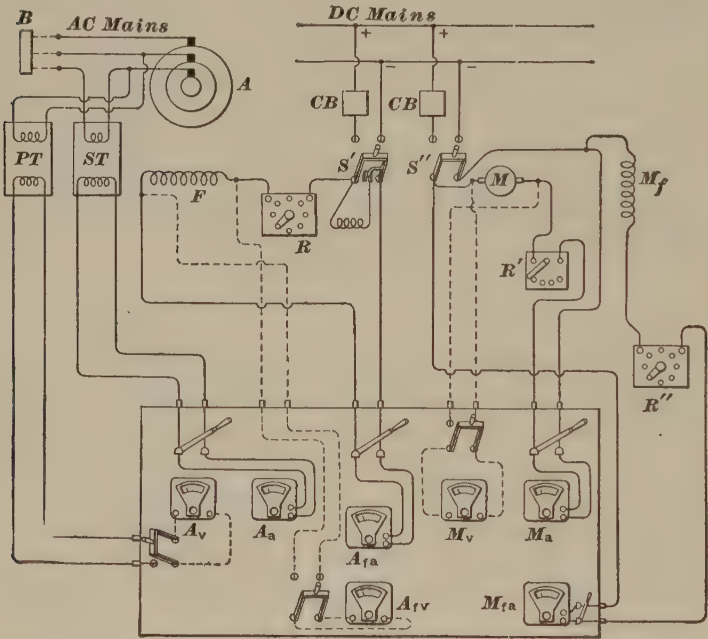


FIG. 12

is shown at M_a; the motor field ammeter, at M_{fa}; and the motor-armature voltmeter at M_v. R' is a rheostat for starting the motor and for adjusting the voltage applied to the motor armature; R'' is a motor field rheostat; M, the motor armature; and M_f, the shunt field of the motor. A form of test sheet suitable for this purpose is shown in Fig. 13 (*a*) and (*b*).

44. Open-Circuited Core-Loss Test.—The driving motor is started, and the alternator is brought to its rated

I L T 362—4

TEST SHEET

ALTERNATOR

*Date*________
*Tested by*________

Rating, 1,500 K. W. Volts, 6,600. Amperes, Line, 131. Amperes, Field, 148.5. Speed, 180. Machine No. 1.

OPEN-CIRCUITED CORE LOSS

Driving Motor								Generator						
Arm. Volts.	Arm. Amps.	Field Amps.	Arm. Res.	Arm. IE Watts	Arm. I^2R	$IE - I^2R$	Speed	Field Volts	Core Loss	Arm. Volts	Arm. Hot Res. Bet. Lines	Field Amps.	Speed	Friction Watts
539	21.5	2.24	.069	11,589	32	11,557	755						180	
550	85.	2.24	.069	46,750	499	46,251	755	80	34,694	6,643	.378	139	180	
535.5	9.2	2.24	.069	4,927	6	4,921	755							6,636

SHORT-CIRCUITED CORE LOSS

Driving Motor								Generator							
Arm. Volts	Arm. Amps.	Field Amps.	Arm. Res.	Arm. IE Watts	Arm. I^2R	$IE - I^2R$	Speed	Core Loss $+ I^2R$	I^2R	Core Loss	Arm. Amps.	Arm. Hot Res. Bet. Lines	Field Amps.	Field Hot Res.	Speed
539	21.5	2.24	.069	11,589	32	11,557	755								180
543	43.5	2.24	.069	23,620	131	23,489	755	11,932	9,739	2,193	131	.378	53.5	.58	180

FIG. 13 (*a*)

EFFICIENCY

Load, per cent.	100	Core loss	34,694
Line volts	6,600	$\frac{1}{3}$ short-circuited core loss	731
Line amps.	131	Armature I^2R	9,739
Field amps.	148.5	Field I^2R	12,790
IR	43	Friction	6,636
$V+IR$	6,643		
		Total losses	64,590
		Output, K. W.	1,497
		Input, K. W.	1,562
		Efficiency, per cent.	95.8

FIG. 13 (*b*)

speed, which should be maintained during the test. The field excitation of the motor should remain constant. The speed of the motor may be adjusted so as to have constant speed under different load conditions by varying the resistance in rheostat R', Fig. 12. Readings of the instruments should be taken only after the speed has been steady for at least 1 minute.

The motor is first made to drive the alternator without any current in the separately excited field circuit of the alternator. Then, readings of instruments M_v, M_a, and M_{fa}, Fig. 12, are taken. The resistance of the motor armature is determined immediately after this test, while the armature is still warm. The readings are then entered in the test sheet.

The number of watts expended on the motor armature is $539 \times 21.5 = 11{,}589$. The watts I^2R loss in the motor armature is $21.5^2 \times .069 = 32$ watts. $IE - I^2R = 11{,}589 - 32 = 11{,}557$ watts, and this power is expended in driving the motor armature and the alternator armature, with unexcited field, and in making up for core losses in the motor armature.

45. The alternator-armature resistance between terminals should be measured while the machine is hot, in case it can be loaded; or measured cold and an allowance made for rise in temperature; in this case, the resistance is .378 ohm.

The drop in voltage at full load, due to the ohmic resistance of the alternator armature, is equal to the line current multiplied by $\sqrt{3}$, and this product multiplied by one-half the resistance between any two terminals of the armature. For a single-phase or a two-phase armature, the drop equals the line current multiplied by the resistance between terminals of the same phase winding. One-half the resistance between terminals of this three-phase armature is $\frac{.378}{2} = .189$ ohm. The rated full-load line current multiplied by $\sqrt{3} = 131 \times 1.732 = 227$ amperes; 227 amperes $\times$ .189 ohm = 43 volts drop in the armature.

46. The separately excited field circuit of the alternator should now be closed. The motor is again started and drives the alternator on open circuit at rated speed. The field current of the alternator is so adjusted as to produce an electromotive force equal to the normal terminal electromotive force plus the full-load armature drop in volts, or 6,600 + 43 = 6,643 volts. Another set of motor readings should then be taken, as well as readings on instruments A_{fv}, A_v, and A_{fa}.

The input to the motor armature minus the I^2R motor-armature loss is now 46,251 watts. Before the alternator field circuit was closed, the corresponding input was 11,557 watts. The difference between these values, 34,694 watts, is the core loss of the alternator on open circuit with full normal electromotive force plus the ohmic drop in volts in the armature. If desired, this test may be made for a number of different values of alternator-terminal electromotive force. A curve of core loss may then be plotted, using watts core loss as ordinates and terminal volts as abscissas.

47. The belt should now be taken from the pulleys, the motor run without load, readings of the motor instruments taken, and the input to the motor armature, minus I^2R armature loss, calculated. This is found to be 4,921 watts. The corresponding input when the motor was driving the unexcited alternator was 11,557 watts. The difference,

6,636 watts, equals the friction loss of the alternator. The friction loss is here considered as the combined bearing-friction and windage loss.

48. Short-Circuited Core-Loss Test.—In order to obtain data regarding the losses in the alternator, due to loading the machine, in excess of the open-circuited core loss, friction loss, and the calculated $I^2 R$ copper losses, a short-circuited core-loss test should be run. The motor is first operated to drive the alternator at rated speed with an unexcited field, and the motor readings noted. The terminals of the alternator armature are then short-circuited, as indicated at B, Fig. 12. The current in the separately excited field circuit is adjusted until the normal full-load current flows through the armature terminals. The motor readings and the readings of instruments A_a and A_{fa} are noted.

The power represented by the difference between 23,489 and 11,557 watts, or 11,932 watts, is expended in core loss and $I^2 R$ armature loss in the alternator; subtracting the $I^2 R$ armature loss leaves the short-circuited core loss. The whole value of the short-circuited core loss is much too great, since the armature current in this test is nearly 90° out of phase with the generated electromotive force and the armature demagnetizing action is excessive; therefore, one-third of this loss is often used in efficiency calculations.

49. If the alternator field current for full load is known, use this value in calculating the $I^2 R$ loss of the separately excited field. If the current is not known, use the square root of the sum of the squares of the field current, obtained in the open-circuited core-loss test at full terminal voltage plus the armature drop, and the field current, obtained in the short-circuited core-loss test at full-load armature current. In this case, $\sqrt{139^2 + 53.5^2} = 148.5$ amperes, approximately, in the field at full load.

The efficiency calculations may now be made from data obtained from the tests and from the calculated $I^2 R$ armature and field losses. These values should be set down in the test sheet, as shown in Fig. 13 (a) and (b).

INDUCTION-MOTOR TEST

50. Preparations for Test.—A simple test to determine the efficiency of an induction motor may be made, in which only one indicating wattmeter, an ammeter, and a voltmeter are required. The test connections for a three-phase induction motor are shown in Fig. 14. By means of the double-throw switch S', one end of the potential coil of the wattmeter W and one terminal of the voltmeter M_v may

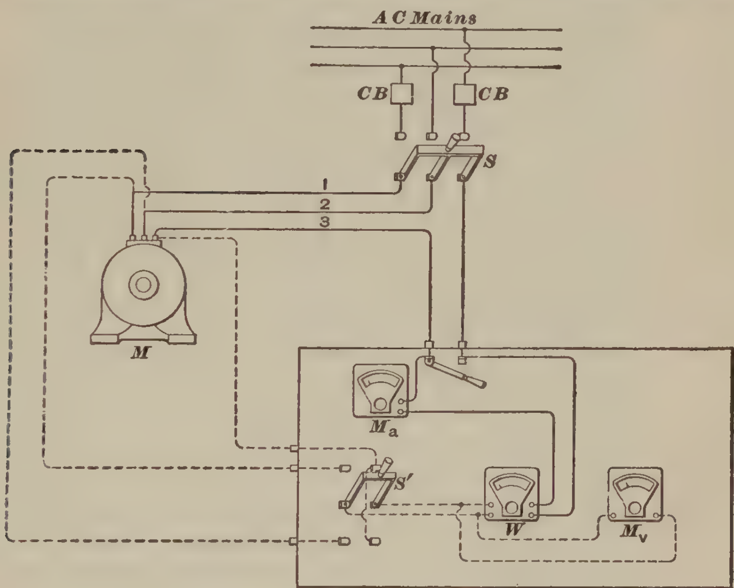


FIG. 14

be connected to either line *1* or line *2*. The other end of the potential coil and the other terminal of the voltmeter are connected to line *3*, when switch S' is closed in either position. The current coil of W is in circuit with line wire *3*.

51. Conduct of Test.—At first the motor is run without load, and the number of watts required to drive it is noted. In the case of an induction motor, the current is out of phase with the generated electromotive force, the power

TEST SHEET

INDUCTION MOTOR

Running-Light Test

*Date*______

*Tested by*______

Rating, 5 H. P. *Volts, 110.* *Amperes, 29.* *Cycles, 60.* *Poles, 8.* *Speed, 900.* *Machine No. 1.*

Total Primary Input $W_1 \pm W_2$	Prim. Res. Bet. Lines	Prim. Amps. Per Lead	Prim. Copper Loss	Core and Friction Loss	Sec. Copper Loss	Rated Output	Losses	Input	Eff. Per Cent.
300	.156	10.4	25	275					
647	.156	29	197		450	3,730	922	4,652	80

FIG. 15

factor is less than unity, and two separate readings of the wattmeter, made in quick succession, are required. One reading is made with the potential coil across lines *1–3*, and the other reading with the potential coil across lines *2–3*. The sum of these readings will give the watts input if the power factor is over .5; if less than .5, the difference in the readings is taken. As previously stated, when two watt-hour meters are used, if the power factor is less than .5, one wattmeter will give a negative reading. The readings are recorded on a test sheet similar to the one shown in Fig. 15. When running without load, the power factor is low, one wattmeter reading is negative, and the difference between W_1 and W_2 is the total watts input.

The primary current may be measured by ammeter M_a, Fig. 14. The resistance of the primary winding between the lines is measured and recorded. The primary I^2R loss is calculated in the manner explained in the alternator running-light test for the alternator armature I^2R loss. Subtracting the primary I^2R loss from the primary input

leaves the core and friction loss, which may be considered constant at all loads.

52. Because of the construction of the rotor, its resistance cannot well be measured. In order to obtain an approximate value of the secondary copper loss, the following test may be made: Clamp the rotor so that it cannot turn. Reduce the electromotive force of the line by lowering the terminal electromotive force of the generator or by inserting equal resistances in the leads to the motor, so that full-load current flows through the primary windings. Take two readings as before, and note the total watts input. The power thus represented is mostly expended in $I^2 R$ losses in stator and rotor. Calculate the $I^2 R$ loss in the stator with the full-load current, and subtract it from the total watts input. The

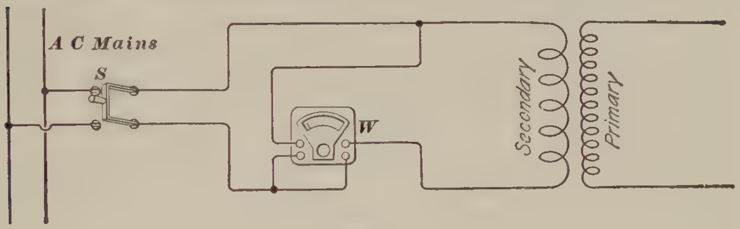


FIG. 16

remainder is approximately the secondary $I^2 R$ loss. There are other small load losses involved in this value of total input, but they may be neglected without serious error.

The full-load current in this case is 29 amperes, and the primary copper loss 197 watts; the total measured input is 647 watts. Therefore, the secondary copper loss is 647 − 197 = 450 watts. The total loss is 197 + 275 + 450 = 922 watts.

53. The output at 5 horsepower is 3,730 watts, the input 3,730 + 922 = 4,652 watts, and the efficiency at full-load 80 per cent. Efficiencies at other loads may be determined by using different values of currents in the primary, when the rotor is clamped, and calculating the copper losses.

TRANSFORMER TEST

54. The core loss of a transformer is obtained by connecting the secondary coil to a line having the *rated frequency* and the *rated voltage*, and measuring the input by means of a wattmeter when the primary is open-circuited. The core loss is practically constant at all loads. Fig. 16 shows the core-loss test connections.

The resistance of either the primary or the secondary coil, at room temperature, is determined by allowing direct current of known value to flow through the coil, and dividing the drop in volts across the coil by the current flowing in it. The windings should not be heated enough during the test to change their resistance. The core losses decrease somewhat with increased temperature, while the copper losses increase, so the resistances at room temperature may be used in the efficiency calculations. The I^2R loss in both coils may be computed for rated full-load current or for partial-load currents. The total loss, aside from some slight losses due to eddy currents in the iron core and in the copper conductors, is equal to the sum of the core loss, with primary open-circuited, and the I^2R losses in the primary and secondary coils. Fig. 17 shows the data of a test for a 7.5-kilowatt transformer.

TEST SHEET

TRANSFORMER TEST

*Date*______

*Tested by*______

Rating, 7.5 K. W. *Type, H.* *Cycles, 60.* *Primary volts, 1,040 – 2,080.* *Secondary volts, 104 – 208.*

Prim. Amps. at 2,080 Volts	Prim. Res. Room Temp.	Prim. I^2R Watts	Sec. Amps. at 208 volts	Sec. Res. Room Temp.	Sec. I^2R Watts	Core Loss Watts	Total Losses Watts	Output Watts	Input Watts	Eff. Per Cent.
3.6	5.65	73.2	36	.0344	44.6	86.5	204	7,500	7,704	97.4

FIG. 17

SWITCHGEAR

Serial 1645 — Edition 1

INTRODUCTION

DEFINITIONS

1. Apparatus used for indicating, recording, controlling, or regulating the output, input, or distribution of electricity is referred to as **switchgear.** A switchboard may have mounted on it various kinds of measuring instruments, switches, fuses, circuit-breakers (commonly called breakers), signal devices, and rheostats; such switchgear is usually *direct controlled.* The use of large apparatus or high voltages may, however, require the location of some switchgear, especially circuit-interrupting devices, in places more or less remote from the switchboard at the control center from which, for reasons of convenience, they may be controlled electrically or mechanically; such apparatus is referred to as *remote controlled.* Controlling devices may require operation by an attendant or may be designed for automatic operation.

REQUIREMENTS OF SWITCHGEAR CONSTRUCTION

2. Safety.—By safety of switchgear is meant freedom from danger to operators or apparatus. Conductors under extremely high electric tension should be kept away from switchboards; the circuit-breakers, fuses, switches, etc. should be of such construction and so mounted as to avoid, as far as possible, the danger of arcs that may burn the operator or throw particles of hot carbon or metal upon him, and to avoid also the danger of arcs that may damage adjacent apparatus.

3. Fireproof Construction.—The supporting structure, insulation, and all other parts of switchgear must be fireproof, in order to avoid the possibility of fires due to electric causes. For this reason, switchboard panels are usually made of marble or of some slate that is free from metallic veins. Insulation that is to be near parts likely to become overheated or that may be exposed to arcs must be capable of resisting high temperatures. Barrier construction made of asbestos board is sometimes installed between high-tension air-break switches and between high-tension busses for this purpose.

4. Capacity.—Knife-blade switches and circuit-breakers too small for their loads are subject to overheating, which draws the temper from the spring copper and makes the contacts poor, a condition that may cause further heating and permanent damage. If the air break of a switch or circuit-breaker is not long enough, an arc may hold across the opening and burn the contacts when the circuit is opened. Oil switches of insufficient capacity, either for current or voltage, may explode if opened under too heavy a load; therefore, they must have capacities far in excess of their normal loads.

5. Accessibility and Simplicity.—All switchgear requires some attention; instruments require calibration, fuses need replacement, and rheostats, switches, circuit-breakers, etc., require inspection, cleaning, and adjustment. In order to make such work safe and convenient, the devices should be readily accessible, but not so much so that at other times they may be a source of danger of physical injury.

Simplicity of construction and arrangement is an aid in operation and tends to reduce the liability of operating errors. The arrangement of the devices should be logical and uniform. Where there are several units of the same kind, as generators, motors, feeders, or circuits, uniformity of switchgear arrangement helps to avoid confusion.

GENERAL CLASSIFICATION

6. Switchgear is divided into two general classes: that suitable for use with direct current and that adapted to alternating current. The line of classification is not very sharp, as some apparatus may be suitable both for direct currents and low-tension alternating currents. Each class is capable of further subdivision into *circuit-opening devices*, *instruments*, *regulating devices*, and *lightning arresters*.

DIRECT-CURRENT SWITCHGEAR

CIRCUIT-OPENING DEVICES

KNIFE-BLADE SWITCHES

7. Circuit-opening devices are used wherever the conductors are to be made discontinuous quickly, conveniently, and, in some instances, automatically. Some of the devices in this class are also used for making the circuit, and all are used as a part of it.

8. Construction.—Knife-blade switches are used in direct-current circuits in capacities of from 10 to several thousand amperes and for all constant-voltage systems. In construction the jaws, or blades, of these switches bear some resemblance to the blade of a knife; each switch blade is hinged at one end and moves in a limited arc in one plane, so as to close into and open from a tight-fitting metal receptacle called a *clip*. Connection on one terminal of the switch is made to the stationary part of the hinge; on the other terminal, to the clip. The connections to these parts are made either on the front or the rear of the base, or panel, on which the switch is mounted. Practically all switches used in switchboard construction have a stud projecting back from each clip through the switchboard panel and another extending from each hinge block.

Electric connection is made to these studs on the back of the switchboard by means of wires, lugs, or copper bars held firmly in place between washers secured by one or two nuts on the studs, the whole being sometimes secured by a jam nut.

9. Varieties.—Knife-blade switches so made and installed as to open a circuit on only one side are known as *single-pole* switches. They may also be made for opening both sides of a circuit, in which case two knife blades are mounted side by side with the axes of their hinges lying in the same straight line and the blades fastened rigidly together by a suitable insulating material, such as dry wood or insulating fiber; switches of this form are designated as *two-pole*. Switches for use on three-wire systems are sometimes made for opening all three conductors at once and are known as *three-pole;* similarly, a *four-pole switch* can be used on a four-wire system.

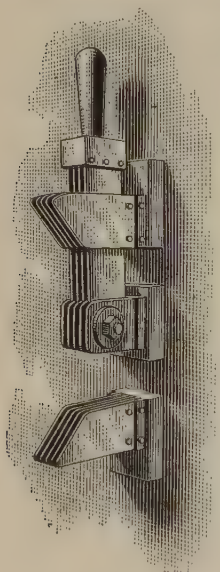


Fig. 1

In addition to performing the duty of opening and closing one circuit, knife-blade switches may be so made as to be selective between two sources of supply or between two circuits. This is done by so constructing the switch that the blade moves through an arc of a half circle and installing a clip at each end of the arc. Such switches are designated as *double-throw* to distinguish them from *single-throw* switches. A single-pole, double-throw, four-blade switch is shown in Fig. 1.

10. Current Densities.—Knife-blade switches are usually made of hard copper or some of the copper alloys. When pure copper is used, the current density through the sliding-surface contacts of small switches may be as high as 80 or 90 amperes per square inch; if alloys are used, the current density allowable is even as much as 50 per cent. lower. In some switches of large capacity, several blades are arranged in parallel, as in Fig. 1, and heat radiation and air circulation are both increased. In

switches of this construction, the allowable current density through sliding-surface contacts is somewhat less, the amount of reduction depending on the number of contact surfaces that are partly enclosed.

Current densities allowable in the contact surfaces of connections to the switch are much higher; because the contacts, being secured firmly by nuts or clamps, instead of by the spring effect of the parts, have better conductivity. Connections between bar copper (draw filed) and cast-alloy nuts properly machined to provide a good surface may have a current density of 120 amperes per square inch. Between cast and machine-surfaced lugs and similar nuts about 110 amperes per square inch is good practice. Connections made with wire usually afford small contact surface unless the wire is flattened where it makes contact with the washers or nuts.

TABLE I

LENGTHS OF AIR BREAK FOR KNIFE SWITCHES

Voltage	Length of Break, Inches	
	100 to 500 Amperes	500 Amperes and Over
50–100	$1\frac{3}{4}$–$2\frac{1}{2}$	2–3
100–175	$2\frac{1}{2}$–3	3–4
175–300	3 –4	4–6
300–700	4 –6	6–8

11. Length of Air Break.—The length of air break necessary for knife switches depends on the current to be interrupted and the pressure tending to maintain the arc. In interconnected networks and other parallel systems the *back feed*, or tendency of parallel circuits to send a reverse current through a broken circuit, reduces to a comparatively small amount the pressure tending to hold the arc. But the back feed cannot always be depended on, and switches with sufficient opening to break a current at the full voltage of the circuit are customarily used. Table I shows lengths of air break that have been found to be good practice.

12. Quick-Break Switches.—Switches that may be required to break large currents at the higher direct-current voltages, 550 to 600, are sometimes made with a device for quickly separating the blade and clip as soon as the circuit has been opened. This construction permits the use of a switch with an air break shorter than would otherwise be desirable. The effect of slow separation of the parts is to cause the arc to hold; when the clip and blade are rapidly separated the effect of the arc is greatly reduced. Fig. 2 shows such a switch of a type in quite general use for street-railway feeders. The blade is in two parts; the main portion *a* carries the handle, and a quick-break portion *b* is held to the main blade by a strong helical spring *c*. Friction of the sides of the clip *d* holds the quick-break blade in place until the main blade has moved into the opening position far enough to put the spring under a tension sufficient to pull the quick-break blade out of the clip. As soon as the latter blade is released, the action of the spring pulls it away from the clip very rapidly.

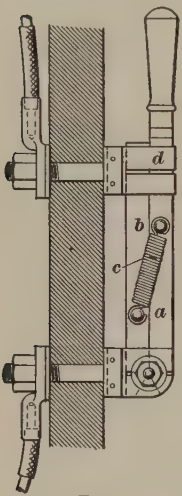


FIG. 2

Another form of quick-break switch, Fig. 3, used for opening the field circuits of electric machines, is provided with a contact *a* in which the blade rests when the switch is open. The switch blade is in two parts hinged on a common axis and connected together by helical springs. When the switch is closed, the main blade *b* rests in the clip *c*; a downward pull on the handle stretches the springs and permits the other part of the blade to make contact with the clip *a* before the switch is completely open. Contact with clip *a* connects a discharge resistance across the field terminals, thereby preventing damage due to

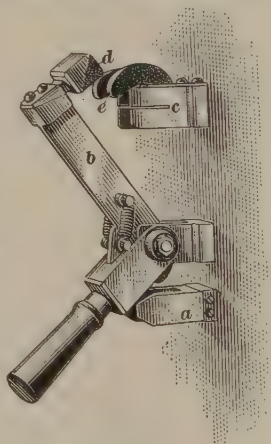


FIG. 3

the high voltage induced in the exceedingly inductive field winding by a sudden interruption of the current. Because of the long, flaming arcs that occur when the current in a highly inductive field winding is broken, the knife blade has an *after break*, consisting of a carbon block *d* and carbon segments *e*, all renewable, between which the arc is formed and broken, thus preventing destructive burning of the more important and more expensive copper parts.

13. Mounting Knife-Blade Switches.—Knife-blade switches should always be mounted within such easy reach that the attendant will be able to exercise sufficient force for positive operation. The operation of knife-blade switches of very large capacity sometimes requires considerable physical effort, and for this reason they should not be mounted with their handles higher than a man's head.

Switches mounted on slate or marble must be set up tight by means of nuts on the studs; but the copper studs should fit loosely in the holes through the panel, because unusual heating may cause a stud to expand enough to crack the marble.

FUSES

14. Open Fuses.—To best perform its duty, a fuse should be of a metal that when fused will not deposit a large amount of molten metal on surrounding parts; it must have a resistance high enough that the passage of the predetermined current will heat it quickly to the fusing point, thus making the *time element* small; and it should present a minimum of surface to be cooled by stray drafts of air. For these reasons a fuse of metal with high conductivity made in small cross-section offers some advantages over those made of alloys with lower conductivities and of larger cross-sections, and copper fuses are quite generally used for breaking currents greater than 150 amperes. For smaller amperages, alloy fuses are generally

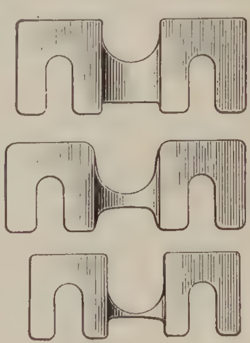


FIG. 4

used on account of the possibility of determining their rating, or fusing, current more exactly than can be done with copper fuses. In connection with low-tension generating and distributing systems, copper fuses are quite generally used; Fig. 4 shows three sizes of such fuses intended for use in a low-tension network where the back feed reduces the potential tending to maintain the arc.

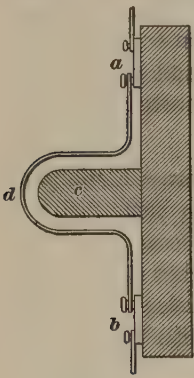


FIG. 5

The length of a fuse must be such that when the metal is melted, and the metallic connection thus broken, the arc will not hold between the fuse-holder terminals. The distance between fuse-holder terminals *a* and *b*, Fig. 5, can be effectively lengthened by putting between them a barrier *c* of fireproof insulating material around which the arc will be forced to pass. The fuse *d* must not touch the barrier, otherwise the latter may conduct away a part of the heat generated in the fusible conductor and thus require a larger current to melt the fuse.

15. Enclosed Fuses.—A method of safely shortening the actual distance between terminals is to enclose the fusible conductor in a shell containing a fireproof non-conducting powder. When the fuse *blows*, or melts, the powder forms a flux with the metal, fills the gap in the conductor, and smothers the arc. Fuses of this form are called **enclosed, or cartridge type, fuses.**

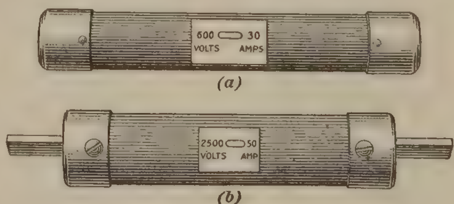


FIG. 6

In order to avoid the necessity of testing to determine whether or not an enclosed fuse is blown, a *telltale*, or indicator, is generally put on the outside. This, in most cases, is merely a fuse of $\frac{1}{8}$ ampere, or less, capacity in parallel with the main fuse. When the enclosed fuse melts, the telltale fuse also blows and burns a small strip of paper pasted over it.

Enclosed fuses are made for currents up to approximately 1,000 amperes. In the smaller sizes, the brass terminals of the fuse are cylindrical, as in Fig. 6 (*a*), and fit into brass or copper clips that partly embrace them. In fuses for more than 75 amperes, the fuse terminal usually consists of a stout copper blade, Fig. 6 (*b*), that fits into a copper clip similar in form to the clip of a knife-blade switch.

CIRCUIT-BREAKERS

16. A **circuit-breaker** is an electromechanical device for automatically opening a circuit in the event of predetermined conditions, such as overload, low voltage, reversal of current, or excessive generator or motor speed. The simpler forms are constructed for automatic opening and manual closing; other forms are provided with controlling devices, such that, in addition to automatic opening, they can be closed and opened non-automatically by remote control at the will of the operator. Some hand-operated circuit-breakers are not built for the final closing of a circuit, and switches should be installed in series with them. Remote-controlled circuit-breakers can also serve as switches, and are sometimes installed without knife-blade switches in series with them.

17. Hand-Operated Circuit-Breaker.—A type of single-pole, direct-current, overload circuit-breaker for hand operation is shown in Fig. 7. Electric connections are made to copper studs *a* and *b* that terminate in large stationary copper blocks on the opposite side of the slate base *c*. The movable system of the breaker is pushed into the circuit-closing position by a lever system, and is held there against the opposition of stiff springs by the latch *d* that engages the handle *e*. The copper blocks are then electrically connected through one or more **U**-shaped, laminated, copper contacts *f* on the movable part of the breaker. Any iron close to the lower stationary contact-block becomes strongly magnetized by the flux established when current passes through the breaker. When the current reaches the value for which the breaker is set, the magnetism becomes strong enough to lift an armature *g* that, in rising, trips the

latch, releasing the handle and permitting the springs to bring the movable system to the open-circuit position shown in Fig. 7. A small handle on the armature provides means for tripping the circuit-breaker by hand.

The unhinged end of the armature is normally supported by the head of a threaded spindle *h* that can be raised or lowered by means of an adjusting nut, thus altering the position of the armature. The higher the normal position of the armature, the shorter is the lift necessary to trip the latch, and the less the tripping current. The spindle is set according to a scale graduated in amperes within the range of adjustment for which the circuit-breaker is designed.

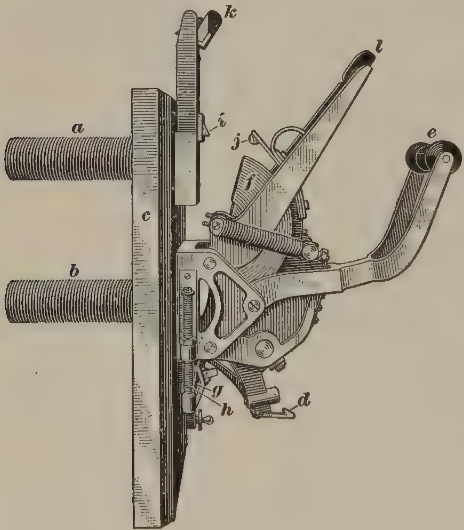


FIG. 7

Some overload circuit-breakers, usually of smaller capacity than the type shown in Fig. 7, are provided with series coils of a few turns of heavy copper capable of carrying the entire current in the circuit. Inside the coil is an iron core that is lifted and trips the latch when the current reaches the value at which the circuit-breaker is set to open. The adjustment of this type of breaker is made by raising or lowering the normal position of the core inside the coil.

18. Arrangement of Contacts.—When the circuit-breaker shown in Fig. 7 is tripped, the main contacts open first, after which the current passes through auxiliary copper contacts to carbon contacts between which the final break takes place. One of the auxiliary stationary copper contacts *i* consists of a

small copper bar with its contact surface inclined to the vertical. The movable contact j leaves this bar immediately after the main contact opens. The lower parts of the contacts k and l are made of copper and attached to the main contacts by heavy copper shunts not visible in Fig. 7. The contact k is so hinged that the lower parts of contacts k and l separate before the upper parts, and the final break, or *after break*, is between the carbon blocks that make up the upper parts of the last-named contacts. The carbon blocks, which are cheap and easily renewed, thus sustain any damage due to arcing.

On some circuit-breakers of large size, the movable carbon after-break contact is so made as to hold against the stationary carbon until the copper parts have moved a considerable distance from the stationary copper blocks, and then to separate very rapidly from the stationary carbon, thus reducing the duration of the arc and the burning of the carbons.

The heat of the arc due to breaking a live circuit causes an air-current that blows the arc flame upwards. For this reason, circuit-breakers of the carbon-break type are always made with the carbon contacts at the top. For the same reason, such circuit-breakers should be mounted at the top of the switchboard; if installed separately, they should be so placed that other apparatus will not be close enough above to be injured by the heat of the arc.

19. Remote-Controlled Circuit-Breaker.—A type of single-pole, remote-controlled, electrically operated, carbon circuit-breaker, of the same general type as the hand-operated device previously described, is shown in Fig. 8. This circuit-breaker is closed by the magnetic action of a solenoid concealed in the housing a. When the closing switch at the control board is thrown so as to complete the control circuit through the solenoid, the plunger b is drawn down; this acts through a system of levers to close the circuit-breaker contacts, which are then held closed by a latch. When the closing switch is opened, the plunger is returned by the springs c to its normal position, where it will not interfere with the opening of the breaker when tripped. The breaker is opened either automatically by an

overload or by a trip coil that receives current at the will of the operator at the control board; in either case, the opening is brought about by springs after the latch has been tripped by the raising of an armature.

Some types of electrically operated circuit-breakers are closed by motors, but these differ from solenoid-operated breakers in mechanical details only.

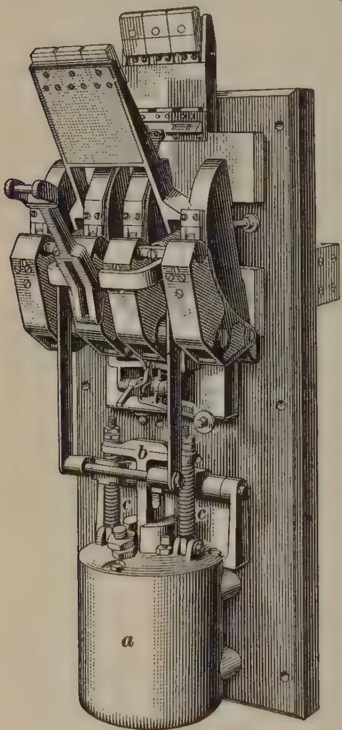


FIG. 8

20. Low-Voltage Release. The low-voltage release is designed to open a constant-potential circuit when the voltage falls below a predetermined value, and consists of a coil of rather fine wire connected across the circuit. When the circuit is at or above the normal voltage, the coil receives sufficient current to maintain a magnetic flux strong enough to hold an iron core against the force of gravity. When the voltage is reduced to the tripping value, the flux is too weak to support the core, which then drops and trips the latch of the circuit-breaker. The device is adjustable by changing the height to which the core can rise in the solenoid.

Circuit-breakers used on 500- or 600-volt circuits generally have external resistances in series with the low-voltage release coils, in order that the coils themselves need not be designed to work on full voltage. The resistance may be mounted in any convenient place, but is generally placed on the rear of the switchboard panel and near the circuit-breaker, in order to shorten the wiring. The low-voltage release can be used on circuit-breakers with or without the overload release.

21. Reverse-Current Release.—One form of circuit-breaker intended for opening a circuit when the direction of current is reversed has in its base a solenoid with a movable core, or plunger, which, when the coil is energized, trips the latch of the breaker. Under normal conditions, this solenoid is not in circuit, but a reversed current of objectionable amount actuates a device that closes the circuit through the coil of a relay that connects the breaker-operating solenoid across the main circuit. In order to protect the breaker-operating coil, which is designed for momentary duty only, a small automatic switch, mechanically connected to the circuit-breaker, opens the circuit through the coil when the breaker operates. The operation and connections of this system are described in more detail in *Electric Substations*.

In some cases, circuit-breakers provided with shunt-operating coils are used for overload service. The breaker is then wired in practically the same manner as when operating on reversal of current, the difference being that the control device is arranged to close the circuit through the relay on overload current in normal direction.

Another form of reverse-current device is operated by a relay that shunts the low-voltage release, which is thereby deprived of nearly all of its current and operates as previously explained.

22. Speed-Limiting Circuit-Breakers.—A speed-limiting circuit-breaker is intended to open the circuit of a motor or synchronous converter when its speed becomes too great. A circuit-breaker having a low-voltage release attachment can be so wired that the operation of a speed-limit device will shunt the low-voltage release coil and thus reduce the current in it sufficiently to permit the core to drop and trip the breaker. The speed-limit device is mechanical in operation, employing a rotatable mechanism driven by the rotor of the machine to be protected. When the speed of the rotating mechanism exceeds that for which the apparatus is adjusted, the device, under the influence of centrifugal force, operates to open the main circuit by shunting the low-voltage release.

The form of circuit-breaker having a shunt-operating coil, as used with the reverse-current relay, can also be employed as a speed-limiting breaker by connecting the contacts of the speed-limit device so that they can close the circuit through the shunt coil.

DIRECT-CURRENT REGULATING DEVICES

STARTING RHEOSTATS

23. Starting resistances for large machines, such as booster motors and synchronous converters, in electric stations and substations are usually made of cast-iron grid units, Fig. 9, mounted in iron frames. Taps from such a resistance are connected to some form of starting switch by means of which the resistance can be short-circuited in steps. A multipoint knife switch is shown in Fig. 10 (*b*). The dotted lines in view (*a*) represent the various positions; as the blade is raised,

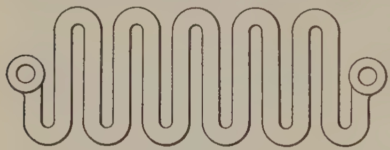
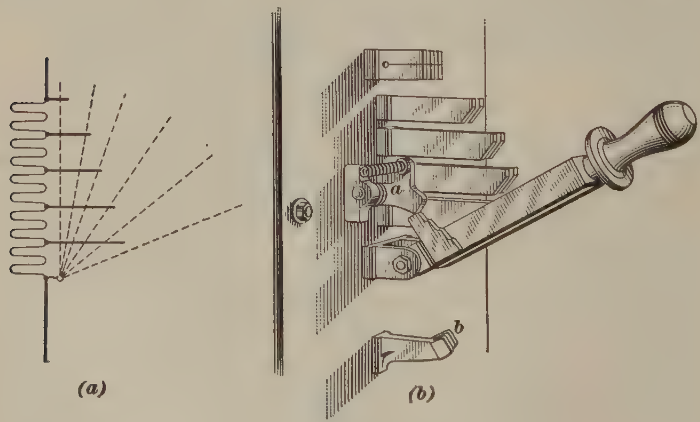


Fig. 9



(*a*) (*b*)

Fig. 10

the clips are engaged, one by one, and the resistance is short-circuited, section by section, until in the vertical position of the

blade the entire resistance is cut out. The pawl *a*, Fig. 10 (*b*), prevents a too rapid notching up; after each movement of the blade, the operator must pause at least long enough to raise the pawl from a notch on the ratchet attached to a blade. The clip *b* has no electric connection; it serves merely as a buffer and as a rest for the blade when in the off-position.

FIELD RHEOSTATS

24. Field rheostats, used for the voltage regulation of generators and the speed regulation of direct-current motors, can be divided into three classes: the *series-resistance type*, *shunt-resistance type*, and *potentiometer type*.

25. The **series-resistance type of field rheostat** is represented diagrammatically in Fig. 11. The arrangement shown in (*a*) is objectionable, because if contact between the rotatable arm *a* and the contact points *b* or between the arm and the contact segment *c* should be broken, the field circuit would be opened. To avoid this difficulty, some series rheostats are connected as shown in (*b*); then if the arm fails to make contact, the field circuit remains closed, but contains all of the rheostat resistance. With the first scheme of connections, the rheostat arm must be wide enough to pass from one contact point to the next without breaking the circuit; with the second scheme the arm should be just as wide, in order to prevent the momentary

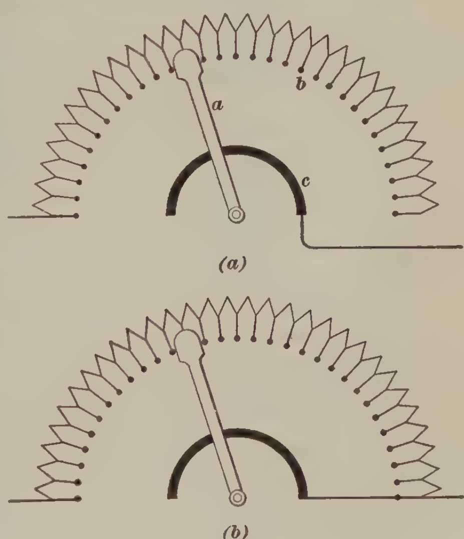


FIG. 11

introduction of the whole rheostat resistance into the field circuit each time the arm passes from point to point.

26. Field rheostats of the **shunt-resistance type,** Fig. 12, are used when it is desirable to be able to reduce the exciting current to practically zero. When the rheostat arm is in position *a*, the field winding is short-circuited; when in position *b*, the entire rheostat resistance is in shunt with the field winding; in any other position of the arm, part of the rheostat resistance is in shunt with the field winding and part in series with it. Here, also, the arm must be wide enough to bridge the gap between adjacent contact points, to prevent opening the field circuit.

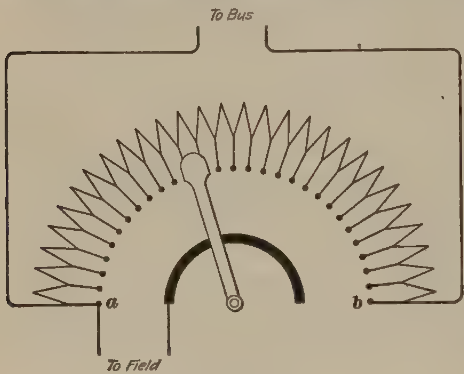


FIG. 12

27. The **potentiometer type of field rheostat,** Fig. 13, a special form of the shunt type, has two arms *a* and *b* that move in opposite directions with respect to the resistance, although mounted on the same spindle and moving mechanically in the same direction. To permit such an arrangement, the contact points are cross-connected, as shown. By means of this type of rheostat, the field current can be lowered from maximum in one direction to zero, reversed, and raised to maximum in the other direction. Such rheostats are used for regulating the excitation of the fields of the series-synchronous-regulating generators of rotary converters and for varying the excitation of the regulating coils of split-pole rotary converters.

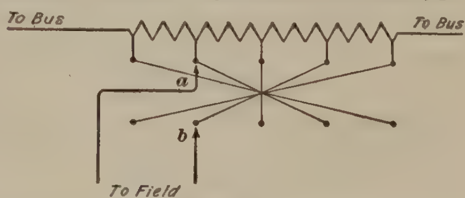


FIG. 13

28. Methods of Field-Rheostat Control.—Small field rheostats are usually mounted directly on the back of the switchboard, as shown in Fig. 14, and are operated by a hand wheel connected to the spindle bearing the contact arm of the rheostat. The rheostat shown in Fig. 14 is of *plate type*, and has three plates in parallel. The weight and bulk of grid type rheostats make it inadvisable to mount them directly on the switchboard; hand control must then be through a system of shafts and bevel gears, as in Fig. 15, or through a chain and sprocket wheels. A hand-operated rheostat should be so

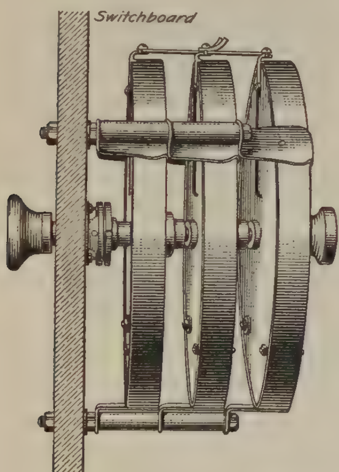


FIG. 14

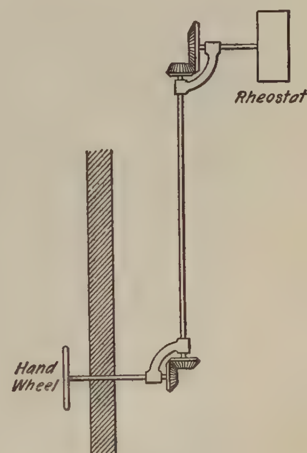


FIG. 15

mounted that the attendant either can see the position of its arm or can determine its approximate place by the position of the hand wheel.

29. When it is desirable to install a rheostat in a position to which mechanical operating devices cannot be conveniently run, the rheostat should be equipped for remote control. A **motor-operated rheostat** is provided with a small motor, usually series-wound, mounted on the rheostat frame and connected to the rheostat spindle through reduction gearing, as in Fig. 16, in which *a* is the motor and *b* the rheostat arm. The motor is controlled by a reversing switch at the switchboard.

30. Another form of remote-control device for field rheostats, Fig. 17 (a), has a ratchet wheel a mounted on the rheostat spindle. Motion is imparted to the wheel through two pawls b and c, one for each direction of rotation and only one of which operates at a time. A reciprocating motion is given to the pawls by the movement of a bar connected to the cores of two sole-

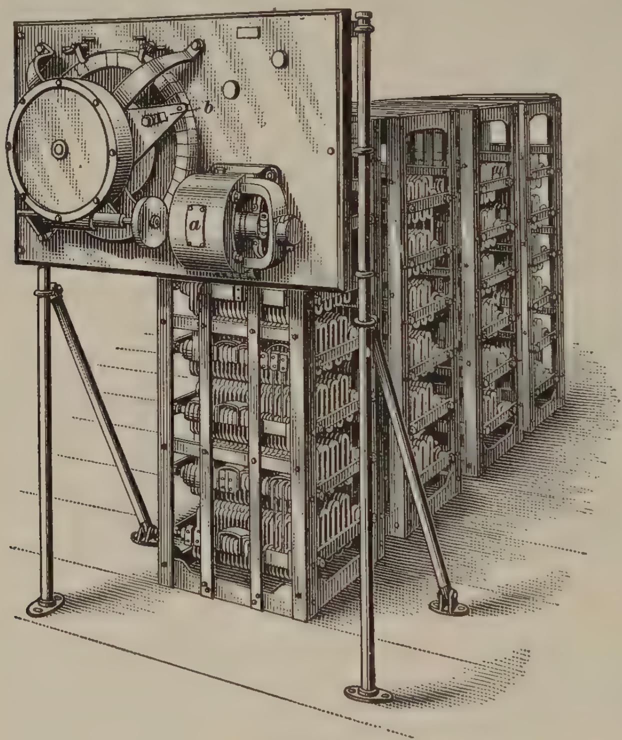
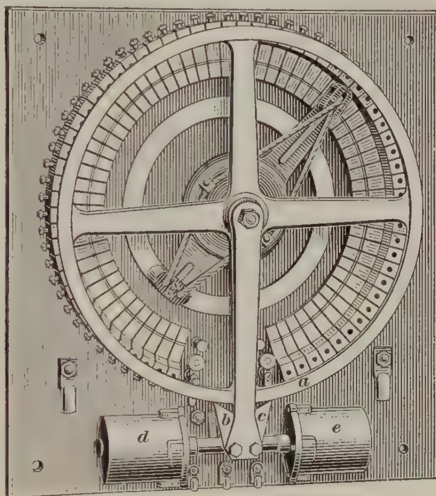


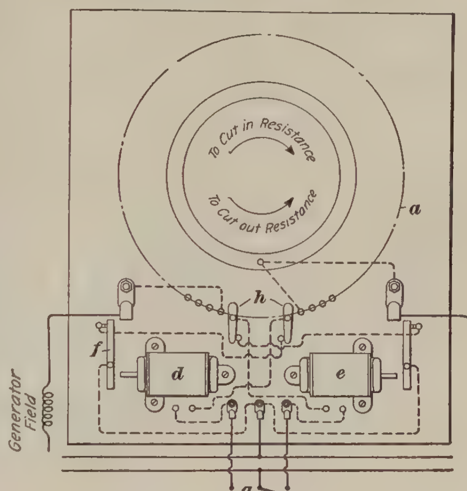
FIG. 16

noids d and e and to a spring. A pull by the solenoid d moves the pawls toward the left, and pawl b pushes the ratchet wheel through a small angle in a clockwise direction. Near the end of the stroke, an extension on the solenoid core engages an interrupter lever f, view (b), the movement of which opens the circuit through the solenoid and permits the spring (not shown) to bring the bar and pawls to the neutral position. This

action continues as long as the single-pole, double-throw, control switch g remains closed to the left. Similarly, by throwing the control switch to the right, the solenoid e can be made active and the rheostat arm rotated in the opposite direction, step by step. In Fig. 17 (a), the interrupter levers are concealed; in (b), the pawls are omitted. At the limit of its movement in either direction, the rheostat arm engages one of two switches h, which opens the circuit through the active solenoid, preventing any attempt to rotate the arm farther in that direction. The other solenoid can, however, be brought into action. The apparatus is thus automatically protected from injury due to leaving either control circuit closed too long. This device can also be used to adjust any remote resistance other than field rheostats, where automatic low-voltage and overload release features are not required.



(a)



(b)

Fig. 17

LIGHTNING ARRESTERS FOR DIRECT-CURRENT CIRCUITS

31. Theory of Lightning Arrester.—Protective devices are necessary to guard electric apparatus against abnormal rises of voltage due to oscillating static charges set up by lightning discharges in the neighborhood of a line, by switching operations, by sudden short-circuits on the line, etc. Apparatus on direct-current circuits is protected by connecting a choke coil *a*, Fig. 18, in series with the lead to each line wire and connecting each lead to the ground through a suitable discharge device, called a **lightning arrester,** at a point beyond the coil. The simple lightning arrester consists of a spark gap *b* in series with a non-inductive resistor *c* of high resistance. The choke coils are of sufficient inductance to keep violent fluctuations or surges of current from entering the station apparatus; the high-potential discharge is forced to take the non-inductive paths through the arresters to the ground. The spark gaps of the arresters are too far apart for the normal line electromotive force to send current across them under ordinary conditions; but the arcs caused by the high-tension discharges so reduce the resistance between the spark points that, were it not for devices that automatically reduce or extinguish the arc, as resistors *c*, the generator would be practically short-circuited and a disastrous after current would result.

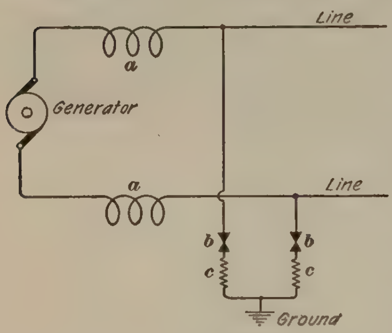


Fig. 18

32. Arresters for Direct-Current Circuits.—Lightning arresters are made for direct-current general lighting and power circuits of 60 to 375 volts, for railway and power circuits of 250 to 2,400 volts, and for series arc-lamp circuits of 2,000 to 6,000 volts.

A type of arrester for use on constant-potential direct-current circuits is shown in Fig. 19 (*a*). The spark points *a* are mounted between two barriers on the cover. When the cover is in place, the contact clips on the spark-gap terminals engage with other clips in the back of the arrester case, thereby connecting the spark gap in circuit between the line and the ground, as shown in (*b*). The coil of an electromagnet *c*, called a *blow-out coil*, is shunted across part of the resistance rod *d*. The pole pieces *b*, view (*a*), of the magnet are extended so that the spark gap is between them. Part of the after current following a lightning discharge is shunted through the blow-out coil and sets up a magnetic flux that acts on the arc between the spark points. The arc, being a flexible conductor, is so distorted, or stretched, by this action that it breaks, or *blows out*. The gases from the arc escape through a hole in the casing.

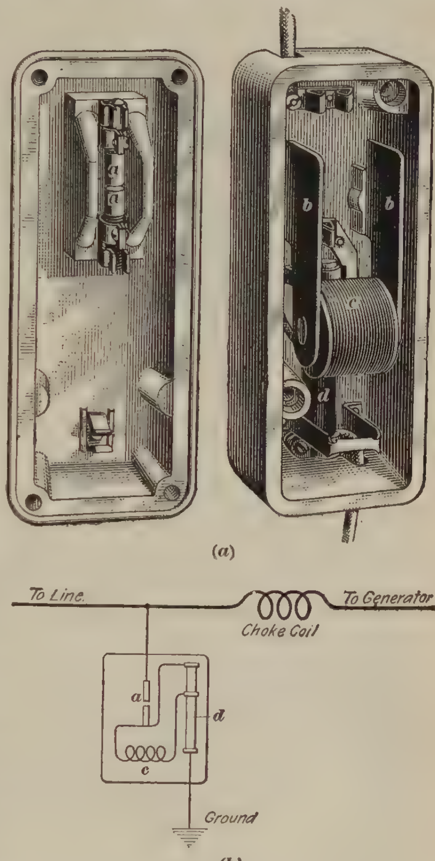


Fig. 19

33. An example of the **horn-gap arrester,** so called from the shape of its spark terminals, is shown in Fig. 20. This type of arrester is used principally on series arc-lamp circuits,

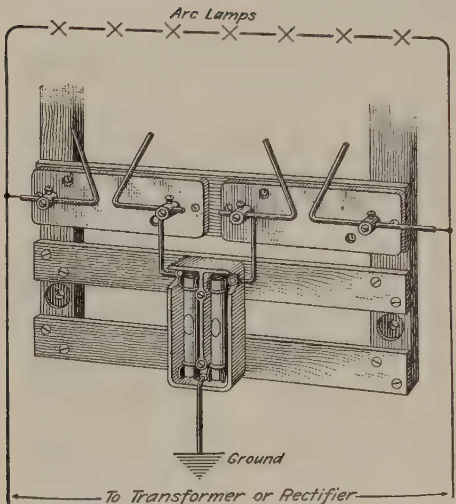


FIG. 20

carrying either direct or alternating current. One terminal of one spark gap is connected to the outgoing line and one terminal of the other gap to the incoming line; the remaining terminal of each gap is connected through a resistance to the ground. The resistors and the shape of the spark terminals are relied on to extinguish the arc at the spark gap. The arc forms at the narrowest part of the gap, but is carried upwards by the rising air-currents due to the heat of the arc itself, until broken in a wider part of the gap, where, due to its increased length, the voltage is no longer able to sustain it. The resistors reduce the after current, as already explained.

In Fig. 21 is shown a form of choke coil used on street-railway overhead feeders. The coil is made of copper rod large enough to carry the full load of the feeder in which it is connected.


FIG. 21

34. Lightning-Arrester Ground Connections.—A well-recommended method of making a ground connection for a lightning-arrester installation is to drive a number of 1-inch iron pipes 6 or 8 feet into the earth surrounding the station and connect them by a copper wire or thin copper strip. To decrease the resistance, a quantity of salt should be

placed around each pipe at the surface of the ground, and the ground should be thoroughly moistened with water. It is advisable to connect the pipes to the iron framework of the station, and also to any water mains, trolley rails, etc. that are available. For the usual-sized station, it is recommended that three pipes equally spaced be placed near each outside wall and three other pipes spaced about 6 feet apart at a point near the arrester. This method of grounding is applicable to installations on either direct-current or alternating-current circuits.

ALTERNATING-CURRENT SWITCHGEAR

CIRCUIT-OPENING DEVICES

KNIFE-BLADE SWITCHES AND AUTOMATIC CIRCUIT-BREAKERS

35. Knife-blade switches of the types described under Direct-Current Switchgear are, without modification, suitable for use on low-tension alternating-current circuits. The current-carrying capacities of small knife-blade switches are the same for alternating current as for direct current; in the medium and large sizes, however, the skin effect is such as to cause a switch to become heated more by a given alternating current than by a direct current of equal amperage.

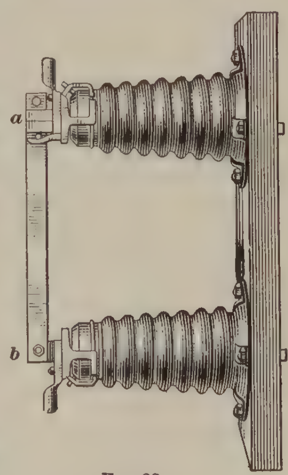


Fig. 22

A form of knife-blade switch for use on alternating-current circuits of voltages up to nearly 50,000 is shown in Fig. 22. These switches are usually mounted high on the board, in order to avoid the danger of personal contact and are operated by means of a long wooden pole with a hook in the end. The distances from the receptacle clip *a* to

the hinge clip *b* range from a few inches up to approximately 2 feet, depending on the voltage. These switches are not suitable for breaking heavy currents.

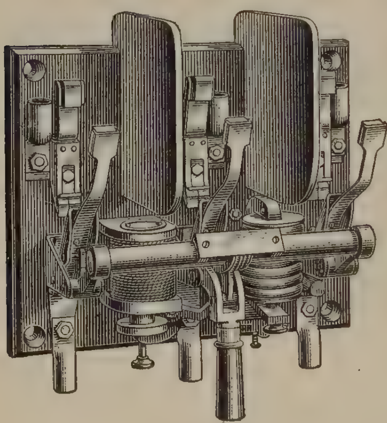


FIG. 23

36. Automatic circuit-breakers, such as are used for direct-current circuits, are, by slight changes, made suitable for use in low-tension alternating-current work. The changes consist of so winding the operating coil that, when alternating current is passed through it, the magnetic flux will be great enough to operate the tripping device. Alternating-current circuit-breakers must, in most cases, open all the phase conductors of a circuit together, and it is therefore common practice to have two- or three-phase circuit-breakers operated by one handle, as shown in the three-phase breaker of Fig. 23.

OIL SWITCHES

37. General Principle.—Knife-blade switches or air-break circuit-breakers are not suitable for use in high-voltage circuits on account of the long and dangerous arcs that are produced when large currents at high potential are broken in air. For such work **oil switches** are used. These are so designed that the actual electric circuit is made and broken under the surface of a high-resistance oil contained in a practically closed vessel. The weight of the oil and its cooling effect combine to smother the arc formed at the instant of breaking the circuit, and the actual length of the arc is reduced to only a fraction of what it would be if the opening were in free air. When the circuit is broken under oil, the arc, though greatly reduced in size, lasts through several cycles, becoming weaker at each alternation and finally being broken at an

instant when the current value is zero. The oil wells are usually made of cast iron or sheet iron lined with wood.

38. Arrangement of Contacts.—On potentials of 4,000 volts or over, it is common practice to open each line of a circuit in a separate oil vessel, or in a separate compartment of one vessel, and to open each line simultaneously in two places by arranging two sets of contacts in series. Fig. 24 shows a

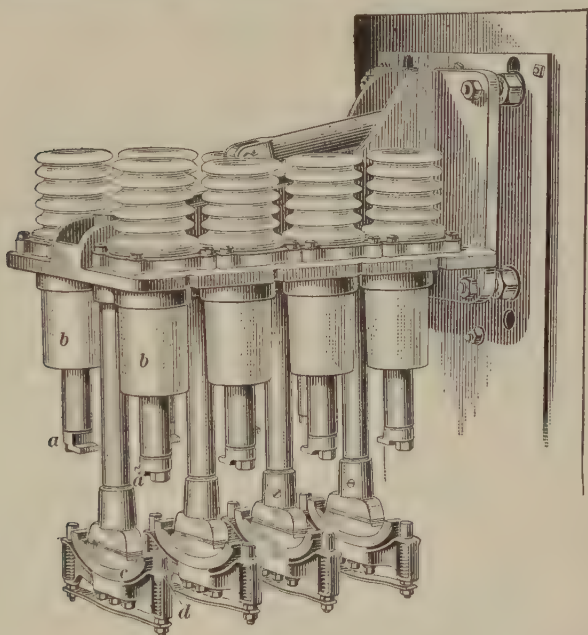


FIG. 24

15,000-volt, 300-ampere, two-phase, oil switch with the oil well removed. Leads are brought to each pair of fixed contacts *a* through porcelain bushings *b* set into the cast-iron cover on the under side of which the oil well is supported. Each movable contact consists of two parts, a main contact *c* of heavy sheet copper brushes and a pair of auxiliary contacts *d* consisting of short, movable, copper cylinders held in place by helical springs. On opening the switch, the final break is at the auxiliary contacts, which take the arc. The movable contacts

are carried on wooden rods, which are caused to move up or down by the operation of a system of levers known as a *link mechanism*. In Fig. 24 the switch is shown in the open position.

The design of the contacts of oil switches is different in switches of various makes and capacities. Some large capacity switches not only open each line in two places but make each break in a separate oil vessel, the mechanism driving each of two vertical rods into a separate oil well, where contact is made inside of a split copper tube.

39. Manually Operated Oil Switch.—Oil switches are operated manually, electrically, or pneumatically. Manually operated oil switches are suitable for use on circuits over which are transmitted moderate amounts of energy. They are operated by a handle connecting through some form of link mechanism to the body carrying the moving contacts. For switches that are mounted on the backs of the switchboard panels the linkage is very short. When it is preferred to place the switches farther away, the link's length is increased and change of direction in their run are made by means of bell-cranks, as shown in Fig. 25.

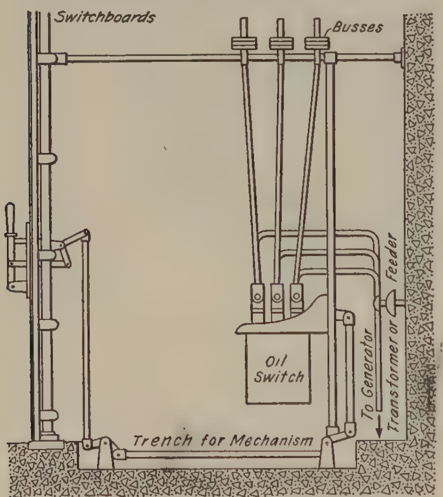


FIG. 25

40. Control Switch.—Electric control of oil switches is obtained by means of direct current supplied to motors or solenoids. Electrically controlled oil switches are generally installed at some distance from the switchboard, which then bears only the control switch and the signal lamps that indicate

if the oil switch is open or closed and whether or not the operation of the mechanism is complete.

In Fig. 26 is shown a form of control switch used for the remote control of motor-operated oil switches and of some solenoid-operated switches. The handle is connected to the blade through a togglejoint *a*. Stops (not visible in the illustration) limit the motion of the blade so that it cannot open farther than the opening clips *b* or close beyond closing clips *c*. In hand operation, the togglejoint is kept straight. When used for automatic operation, the predetermined load conditions, such as overload, underload, low voltage, etc., are caused to operate a relay that sends current through a small solenoid in the rear of the switch. The solenoid drives a plunger *d* against the togglejoint, breaking the toggle and allowing the springs *e* to pull the blade into the opening position. The signal lamps *f* indicate to the operator whether or not the oil-switch movement is completed and the current supply properly cut off from the operating device.

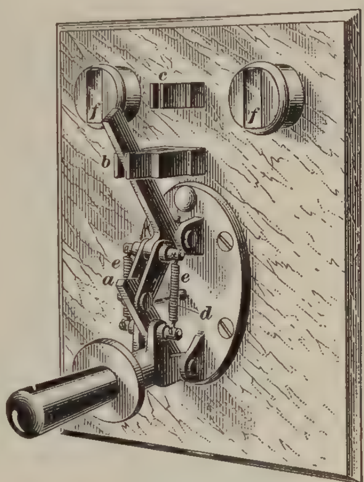


FIG. 26

41. Motor-Operated Mechanism.—In Fig. 27 is shown a motor-operated oil-break switch mechanism. The direct-current motor *a* is connected through a magnetic clutch *b* to a worm-gear that rotates a crank forming one point in a *pantograph*, or straight-line, motion. The crank connects through a system of levers to arms *c* that carry vertical rods (not shown in Fig. 27) bearing the contact forks that make or break the main circuit. The vertical rods pass through the top of the concrete or brick structure forming the fireproof compartments in which are erected the oil tanks of the switch. Fig. 28 shows

the general arrangement of a complete three-phase switch, with the doors of the fireproof compartments omitted so as to reveal the interior of the compartments.

The motor starts the mechanism and causes it to pass a dead center, after which powerful coil springs drive the device, almost, but not quite, completing its movement. While the

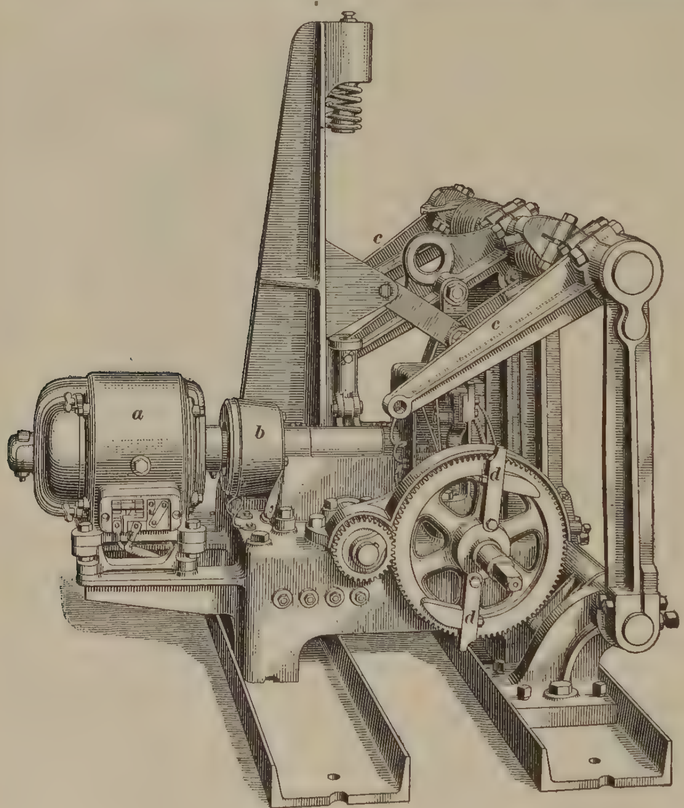


FIG. 27

springs are operating the mechanism, the motor continues to rotate, but runs free. When the operation of the springs is complete, the motor engages the shaft through a mechanical clutch, completes the switch movement, and winds the springs to tension for the next operation. At this juncture, a cam

on the rotating shaft of the pantograph motion operates a cut-out master finger, which opens the control circuit and thereby causes the magnetic clutch to release. The master finger is held against the cam surface by springs.

A projection *d*, Fig. 27, that rotates with one of the speed-reduction gears catches on a projecting part of the mechanism if the switch, in opening, should continue its motion too far and begin to close, a condition that might result if the cam controlling the master finger were out of adjustment or if the magnetic clutch should fail to release. The establishment of the control circuit operates a magnet that draws back the engaging projection during normal operation of the mechanism.

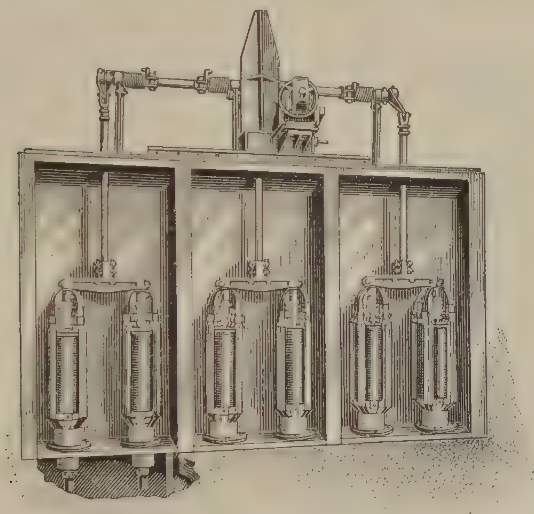


FIG. 28

42. Solenoid-Operated Mechanism.—A type of large, solenoid-operated, oil switch is shown in Fig. 29. Powerful solenoids *a*, when energized by current in the control circuit, move iron cores *b* a short distance. The ends of the cores connect through sprocket chains to a system of levers carrying the contact-making parts, which are similar in design to those of the hand-operated switch shown in Fig. 24. The switch,

Fig. 29, is shown with the oil wells removed and without the brick or concrete barriers. One of the three oil tanks required for this switch is shown at *c* and its supporting pedestal at *d*. In addition to the pedestal support, the tanks are clamped to the casting *e*. Leads *f* and *g* of the large and small conductors are connected to the main and control circuits, respectively.

43. Pneumatic Operation.—Oil switches operated by compressed air are not used to as great an extent as those worked by electricity. The mechanism that has air for its operation is used where remote control is desired, but where direct current is not conveniently available.

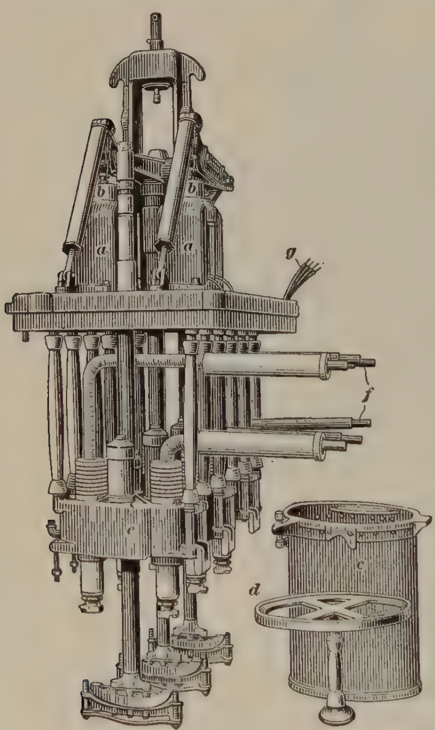


FIG. 29

One type of switch mechanism put in action by means of compressed air is practically identical with machinery of the same type that has the solenoid for its operation except that the latter is replaced by a diaphragm arrangement actuated by compressed air. The air is controlled either by hand-operated or by electrically operated valves. Each switch is supplied from an auxiliary tank that receives air from a main storage tank. A compressor driven by an alternating-current motor furnishes the air supply.

44. Automatic Operation.—Oil-break switches provided with automatic devices for opening the circuit when the current

exceeds a predetermined amount are practically high-tension circuit-breakers. The primary of a current transformer is connected in the main circuit; the secondary is in series with the coil of a relay by means of which a direct-current circuit is closed through the operating device of the oil switch. Hand-operated oil switches with automatic release are provided with a spring-and-toggle arrangement; current through the solenoid, or trip coil, of the operating device raises a plunger that breaks the toggle and allows the spring to open the switch. In motor- and solenoid-operated oil switches the relay performs the same service as the control switch.

Some hand-controlled oil switches are operated without a relay, the secondary of the current transformer being connected in series with the trip coil of the switch. Switches of this kind do not require direct current for their automatic opening.

45. Example of Overload Relay.—An overload relay for use in connection with the operation of high-tension oil switches as circuit-breakers is shown in Fig. 30. A coil within the casing *a* is connected in series with the secondary winding of the current transformer and is designed to carry about 5 amperes at normal load on the main circuit. When the current in this coil exceeds the amount for which the relay is adjusted, a cone-shaped contact *b* is raised, by a movable core, into contact with two stationary fingers *c*, completing the circuit through the opening device of the oil-switch-operating mechanism.

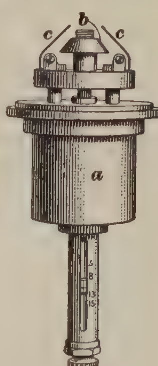


FIG. 30

46. Time Element in Relay Action. Circuit-closing and circuit-opening relays are made in three types.

Instantaneous relays operate almost instantly on the occurrence of the condition, such as overload, that the relays are to control.

Inverse time-limit relays can be adjusted for a delay between the occurrence of an overload and the closing of the

relay contacts, the extent of the delay being approximately inversely proportional to the magnitude of the overload. When the type of relay shown in Fig. 30 is designed for inverse time-limit operation, the upward motion of the core with its contact-making cone is opposed by a small circular diaphragm, or bellows, within the casing at the top. On being pushed inwards by the core, the bellows forces air out through a set of narrow passages. The time required for the operation of the relay with any given current is regulated by adjusting the size of the air passages.

47. In the **definite time-limit type of relay,** the time limit is practically constant for any given setting under ordinary conditions of overload or short circuit. When adapted to definite time-limit operation, the relay just described has a compression spring interposed between the movable core and the diaphragm. In rising, the core compresses the spring and further motion of the core is prevented by a stop, making the relay practically independent of the amount of the overload; only the stored energy in the spring, if the overload continues, applies power to the diaphragm. If the overload comes on so slowly that the spring is not fully compressed at once, the time limit will vary slightly. If, therefore, the scheme of operation requires protection against a creeping, or comparatively slowly increasing, load an instantaneous relay is used to close the circuit through the solenoid of a definite time-limit relay.

48. Reverse-Current Relays.—In some cases relays are used to open the oil switch automatically when the direction of energy flow is reversed. Such a relay has two coils, one in series with the secondary of a current transformer and the other supplied from the secondary of a potential transformer. Ordinarily, the only force tending to move the contact-making part is that due to the difference of the magnetomotive forces of the two windings. When the energy flow is reversed, the force tending to move the contact-carrying device is that due to the sum of the magnetomotive forces. Reverse-current relays are made for instantaneous, definite time limit, or inverse time-limit operation.

HIGH-TENSION FUSES

49. General Features.—Although automatically operated oil switches are better for opening a circuit than fuses when any large amount of energy in the form of a high-pressure current is to be interrupted, the cost of oil switches sometimes leads to the use of high-tension fuses, which are made long, and on account of their small current capacity are small in cross-section. In order that the arc formed at the moment of fusing shall be interrupted, springs hold the fuse strip under tension, and, as soon as the metal becomes hot enough to be nearly melted, the springs break the fuse and rapidly separate the ends. In order to prevent the arc from jumping to near-by apparatus and to smother it as much as possible, the fuse and springs are nearly enclosed.

FIG. 31

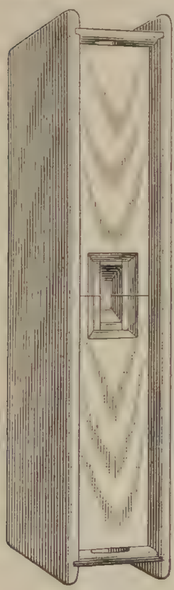


FIG. 32

50. Examples of High-Tension Fuses. In one form of high-tension fuse construction the aluminum fuse strip, Fig. 31, lies between blocks of wood, as in Fig. 32, except at the part of narrow section where the blowing occurs. The blocks serve to prevent the arc from following the broken ends as they are pulled by the concealed springs.

51. High-tension fuses for use with a potential transformer of 6,600 to 60,000 volts are made to carry only a small current, usually not more than about ½ to 1 ampere. One form, Fig. 33, consists of a hard fiber tube, of a length adapted to the voltage of the circuit, bearing on the outside of one end a small metal ferrule and on the other end a brass bulb. The fuse wire is fastened by screws to the ferrule at one end and to the bulb at the other. The space within the bulb is an explosion chamber in which the fuse can blow. In order that the blowing will occur in the chamber rather than in the tube, the fuse

metal is smaller in cross-section in the former than in the latter. When the fuse blows, the explosion with the consequent expansion of the gases formed in the bulb, projects the arc out through the open end of the tube and opens the circuit. New fuses can be inserted into the holder, and a hook with a wooden

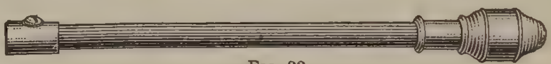


FIG. 33

handle is provided to remove the holder from the contact clips. The method of mounting this type of fuse on a potential transformer is shown in Fig. 34. The *expulsion fuse*, as the type is commonly known, with slight modifications in construction, is also used for other purposes.

52. Another type of high-potential fuse is made for use on circuits of 10,000 volts and higher. The fuse metal is held under tension by a spring, and both spring and fuse metal are immersed in an insulating and fireproof solution that fills a

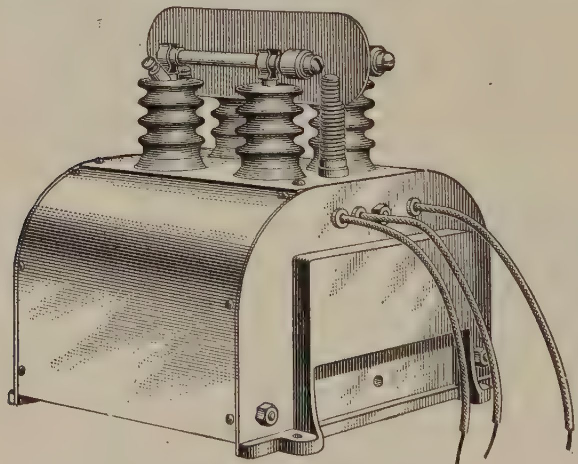


FIG. 34

glass tube. When the fuse blows, the gap is immediately lengthened by the springs, which pulls the lower end downwards. In addition, the arc is immediately extinguished by means of the liquid in the tube.

ALTERNATING-CURRENT REGULATING DEVICES

53. The voltage regulation of alternating-current circuits is of such importance that an entire Section has been devoted to that subject. Therein are described apparatus that are logically classed with switchgear and would, except for their importance and the consequent space necessary for a proper explanation of them, be described here.

LIGHTNING ARRESTERS FOR ALTERNATING-CURRENT CIRCUITS

PURPOSE

54. Lightning arresters for use on alternating-current circuits are intended to protect the apparatus in the station or substation from high-frequency disturbances, either in the form of lightning or of high-frequency waves caused by surges or open-air arcs. They discharge high-frequency disturbance and prevent an unduly large potential from developing either between conductors or between conductors and ground, and they must prevent the current of the circuit from following the path of the high-frequency discharge to ground.

MULTIGAP ARRESTER

55. Action Across Gaps.—In Fig. 35 is shown a 2,200-volt **multigap arrester, with graded shunt resistance.** The arrester has thirteen air gaps between knurled cylinders of a special, so-called *non-arcing metal*, an alloy containing a metal of low boiling point and one of high boiling point. The cylinders act like plates of a condenser, each cylinder on being charged inducing a charge on the next. If the potential becomes high enough, the first cylinder discharges to the second by a spark across the air gap, and thus the second cylinder becomes charged almost to line potential; the next gap breaks down

and the discharge continues across the gaps successively to the grounded terminal of the arrester.

The line current follows the static discharge and jumps across the gaps, which now have a greatly reduced resistance. This action continues until the electromotive force passes through zero in reversing. Before the electromotive force can establish a reversed current, the arc vapor cools to a non-conducting state.

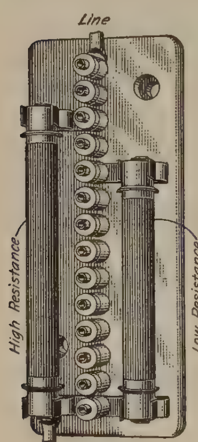


Fig. 35

An arrester with a series of small gaps discharges at a much lower voltage than an arrester with a single gap of a length equal to the sum of the small gaps. At the same time, there are enough gaps to insure the extinguishing of the arc that follows a discharge.

56. Action of Graded Shunt Resistance.—A resistance in series with the air gaps of an arrester may limit a static discharge to such an extent that an arrester with a series resistance will fail to give protection against a destructive rise of voltage under severe conditions. An arrester with graded shunt resistance, however, gives paths among which a discharge of any frequency can find a low-impedance passage to the

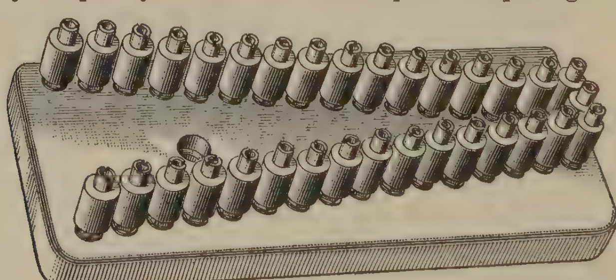


Fig. 36

ground. In the arrester shown in Fig. 35, for instance, one path—high resistance and two series gaps—is for discharges of low frequency or for discharging a gradual accumulation of

static electricity; a second path—low resistance and four series gaps—is for discharges of medium frequency; and a third path—gaps only—is for discharges of extremely high frequency. When the gaps of an arrester are shunted by even a low resistance, discharges of very high frequency (hundreds of thousands, or, possibly, millions, of cycles per second) find it relatively difficult to overcome the impedance of the resistance rods, but comparatively easy to pass across all the gaps, owing to the condenser effect.

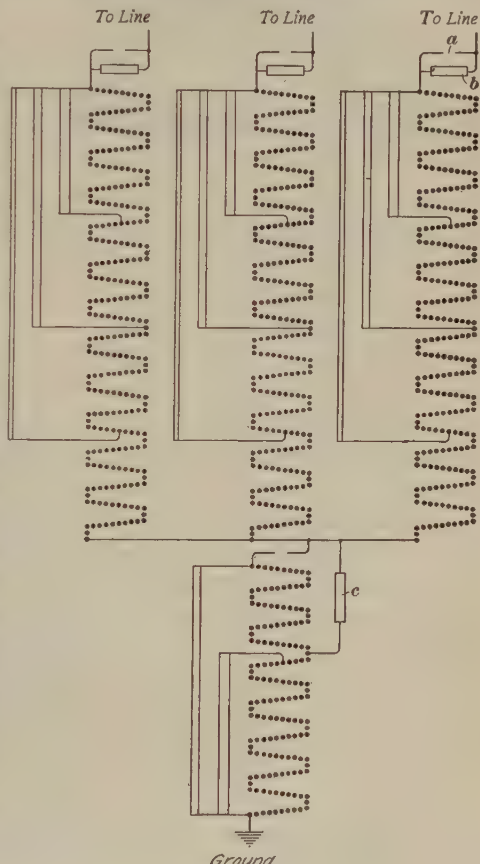


Fig. 37

The shunt resistances also assist in the prevention of arcing. It is shown by tests that whenever a number of gaps are shunted by a resistance of less than a certain ohmic value per gap, the dynamic current will take the path through the shunt resistance, even when the heaviest static discharges pass across the shunted gaps.

57. High-Voltage Multigap Arrester.—High-voltage multigap arresters are made up of units, Fig. 36, in which the knurled cylinders are arranged diagonally in order to save space, for a high-voltage arrester requires a large number of gaps in

series. The cylinders are mounted on porcelain, which insulates them from one another. Units are connected together by short, metal strips.

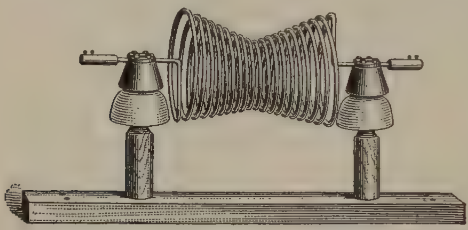


Fig. 38

In Fig. 37 are shown the connections of a graded, shunt-resistance, multigap arrester for a 33,000-volt delta-connected, or ungrounded Y-connected, three-phase system. The fourth arrester leg, between the common connection of the other three legs and the ground, is necessary because without it, if one line conductor becomes accidentally grounded, the full line voltage will be thrown across one leg of the arrester. On a Y system with a grounded neutral, this ground leg is omitted because on such a system an accidentally grounded phase wire causes a short circuit of that phase and the arrester is relieved of the stress by the tripping of the circuit-breaker.

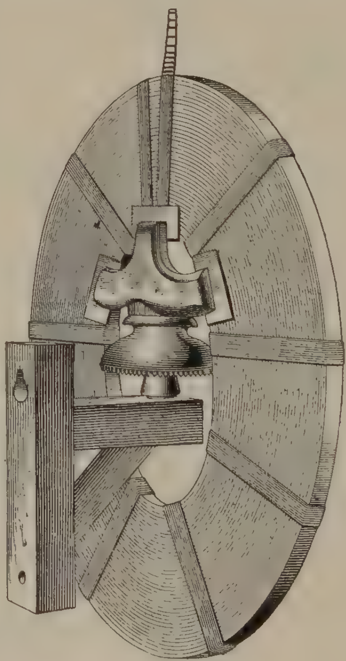


Fig. 39

An auxiliary adjustable gap *a* between each line wire and the corresponding arrester leg is necessary to take care of particularly severe abnormal conditions. Each auxiliary gap is short-circuited by a fuse *b*, so that it comes into service only when the fuse blows on account of an arc between phase wire and ground or because of some similar extremely severe continued stress. The sensitiveness of the arrester is also greatly

increased by a similar fuse *c* shunting an auxiliary adjustable gap and part of the main gaps of the ground leg. These fuses must be inspected frequently and replaced when necessary.

ELECTROLYTIC ARRESTER

58. The **aluminum-cell,** or **electrolytic lightning arrester** has the advantage of a very large discharge capacity, and can be made to discharge when the pressure on the lines has increased by only 10 or 15 per cent., thus protecting the apparatus against high potential due to surges, as well as to lightning. Aluminum-cell arresters can be installed either indoors or outdoors as may be most convenient, although they are recommended for indoor installation, as the electrolyte freezes at a temperature of about 20° F.

CHOKE COILS

59. Choke coils used on alternating-current systems usually have only a few turns, but these have impedance enough to choke back the high-frequency waves of a lightning discharge. For circuits operating at voltages up to 6,600, cylindrical coils of insulated wire mounted on a marble base are usually employed. For voltages above 6,600, bare wire wound into the shape of an hour glass, Fig. 38, is used. The flat spiral, or *pancake*, coil of Fig. 39 is made of insulated strip copper and has considerably more reactance than the other two forms.

THE ASSEMBLED SWITCHBOARD

DEFINITION AND GENERAL REQUIREMENTS

60. To be used most conveniently and effectively, the various devices comprising switchgear must be suitably arranged with respect to one another. Usually switches, relays, and instruments are mounted on slate or marble panels, in the rear of which are the copper busses, ties, machine leads, feeder leads, instrument leads, etc., connecting the several parts and devices of the generating and transmission system.

The combination of slate or marble panels, switches, instruments, busses, and instrument leads is referred to as the **switchboard.** The switchboard is the center from which the greatest part of the electric machinery of a station is controlled. The connections should be as simple and as easily traceable as the requirements will permit.

It is the general practice to set all of the panels in a straight line when there is sufficient space. Some instruments, such as voltmeters and synchronizing indicators, which must be observed when performing operations at various places on the switchboard, are put on *wing panels* set at an angle with the main line of the switchboard.

PRESSURE WIRING

61. Small wiring connected to instruments, control switches, relays, and the like, is sometimes called **pressure wiring.** Such wiring is generally mounted on the rear surface of the switchboard panels, where it is fastened in place by small fiber or hard-rubber cleats held by screws driven into wooden or lead plugs set in the marble or slate.

In pressure wiring, conductors with a considerable difference of potential between them may be placed side by side; it is therefore important that the conductors be well insulated, and it is desirable that the insulation be flame-proof.

DIRECT-CURRENT SWITCHBOARDS

ARRANGEMENT OF SWITCHGEAR

62. In direct-current switchboard design, it is better to have a separate switchboard panel for each generator or motor unit; if two panels per unit are required, they are usually placed side by side.

Circuit-breakers are put at the tops of the panels so that the arc which is formed when they open will not affect any of the other switchboard apparatus.

If heavy currents are carried on the busses, the switchboard instruments, unless provided with heavy magnetic shields, must not be placed in such positions as to be affected by the magnetic field around the busses. An instrument not heavily shielded magnetically should not be mounted nearer than about 6 inches from a bus carrying 400 amperes, 8 inches from a bus having a load of 1,600 amperes, or 14 inches from a bus carrying 2,500 amperes.

The switches are directly under the circuit-breakers, but far enough away so that flying particles of hot copper, or carbon from the latter may not be thrown into the faces and eyes of the operating men. The instruments are placed where they can be observed easily by the operator when he closes the switch.

BUS-BARS

63. Copper bars used for direct-current busses are generally uninsulated, as it is impracticable to insulate all of the current-carrying parts, and to insulate some might lead to a false sense of safety.

Bus-bars should be supported at a distance of 8 to 12 inches in the rear of the panels and mounted on firm insulators set on brackets fastened to the structural-iron frame that supports the switchboard. If of a capacity as large as 3,000 amperes, the busses should be made of two or more wide thin copper bars spaced about $\frac{1}{4}$ inch apart, in order to give better ventilation and more surface for the radiation of heat than could be obtained by the use of one large, thick bar.

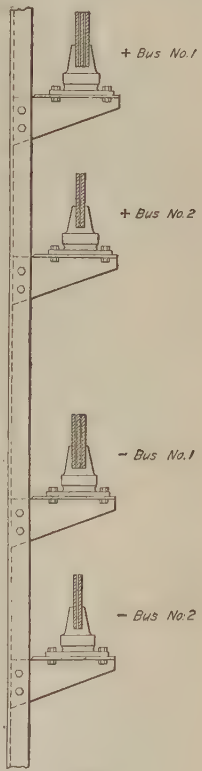


FIG. 40

64. Air Circulation.—Air circulation between the individual bars of a bus is best when they are set on edge, as shown in Fig. 40. This method of setting busses is, however, objectionable for two reasons: The rear surfaces of panels are

rendered difficult of access for installing, repairing, or changing the small wires that are fastened to the panels; also, when busses of different polarity, or several busses of like polarity, but of unlike voltages, are together in the rear of the same panels, the distance between adjacent busses is rather small if the edgewise arrangement is used, thereby increasing the danger from short circuits. For these reasons, some engineers prefer to lay the bars flat, as shown in Fig. 41, compensating for the reduced ventilation by increasing the cross-sectional area of the busses.

Fig. 41

65. Current Density in Busses.—To prevent heating of the bars, the current density in copper busses should be rather low, especially if they are long, either continuous, or made up of sections firmly bolted together. Heating causes expansion, which puts undue stresses on the studs of switches and on the jumpers between them and the bus-bars. Bus-bars set on edge should not have a current density of more than 1,000 amperes per square inch of cross-sectional area; for bars laid flat, 950 amperes per square inch has been found to be the allowable maximum.

66. Joints in Busses.—A form of construction in quite general use for making joints in busses is to overlap the copper bars but not to bolt them. The bars are held in good electric contact at each joint by a three-cornered clamp set up by bolts. This method allows for expansion and contraction, and relieves a part of the stress on the jumpers and switch studs.

67. Separation of Busses of Unlike Polarity.—Busses of unlike polarity should be separated in such a manner as to make it difficult to start a short circuit by making an electric contact between them. When both the positive and the negative busses are on the same switchboard, the separation is sometimes made by putting all of the negative busses near the lower part and the positive busses near the top, as shown in Fig. 40. Sometimes the positive busses and switches are on

one switchboard and the negatives on another with an aisle between them.

The switchboard should never be set up so close to a wall that it will be difficult to work in the rear of it. The space between the wall and the busses should not be less than 3 feet, and a space of 5 feet is better.

ALTERNATING-CURRENT SWITCHBOARDS

DIRECT-CONTROL SWITCHBOARDS

68. Direct-control switchboards for alternating current are used in plants of small or moderate capacity (50 to 750 kilowatts) operating at voltages ranging from 240 to 3,000. The oil switches are usually secured to the back of the board, with the operating mechanism extending through the board to connect with the operating handle in front. The oil switch is usually supported on a bracket, either bolted directly to the slate or marble panel, or clamped to the framework, as shown in Fig. 42.

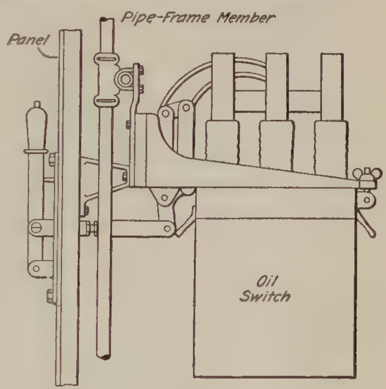


FIG. 42

The bus-bars are usually supported on porcelain insulators clamped to brackets near the top and in the rear of the switchboard. This location places the bus-bars out of danger and leaves room for the ready inspection or repair of the oil switches and their control mechanisms.

REMOTE-CONTROL SWITCHBOARDS

69. In stations of large capacities and greater voltages, instruments and relays are operated by the secondary currents from the instrument transformers instead of directly by current

from the main circuit, and the location of the main-circuit connections on or near the switchboard is unnecessary. Requirements of safety, space, fireproofing, etc. also make desirable the removal of high-tension apparatus and connections from the switchboard.

70. Mechanical Arrangement.—The simplest system of remote control is the mechanical arrangement shown in Fig. 25. The aisle between the switchboard and the oil switches should be wide enough for work to be safely performed on the switches or on the rear of the board. The bus-bars should be high enough to be out of reach, and high-tension leads from the oil switches should be insulated. Instrument transformers are usually mounted on the wall back of the switches.

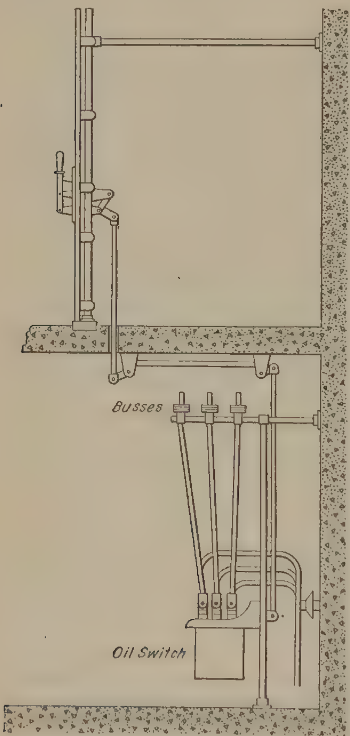


Fig. 43

Sometimes, the switchboard is erected on a gallery overlooking the machinery and the oil switches and busses are installed on the machine floor, as in Fig. 43. A similar arrangement is used when the switchboard is installed on the main floor and the oil switches and busses are placed in the basement.

71. Electric Control. When the oil switches and the bus-bars are installed at a considerable distance from the switchboard, electric control of the oil switches is employed. Control current is carried from the direct-current operating busses on the switchboard to the oil switches, sometimes installed in a special switch room, through control leads, as shown in Fig. 44. The control leads are usually carried in conduit.

Direct-control and mechanically operated, remote-control switchboards are generally arranged with the generator oil switches and switchboard panels at one end of the busses and the feeder switches and panels at the other end; the switches are in line with the panels. In electrically controlled systems, also, the switchboard is conveniently arranged with the panels grouped together in exciter, generator, and feeder sections. The oil switches, however, need not be so grouped; that is, it is not necessary for all the generator switches to be placed at one end of the busses and all the feeder switches at the other. In some installations, this flexibility is of considerable advantage.

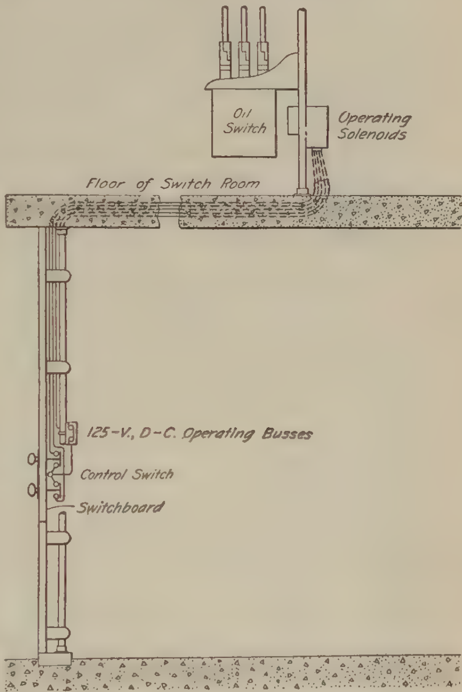


FIG. 44

72. Arrangement of Bus-Bars. Bus-bars are not always arranged in a horizontal plane, as in Figs. 25 and 43, and the bars are not always rectangular in cross-section. In one form of bus-bar construction for 4,000-volt circuits, round bars are wrapped with about $\frac{1}{2}$ inch thickness of high-grade insulation possessing great dielectric strength. The bars are supported one above the other by wooden bushings secured to the vertical members of the steel frame that supports the oil switches.

In high-tension systems, the bus-bars are supported on large porcelain insulators and separated by brick, asbestos board,

or concrete barrier construction, as shown in Fig. 45. The

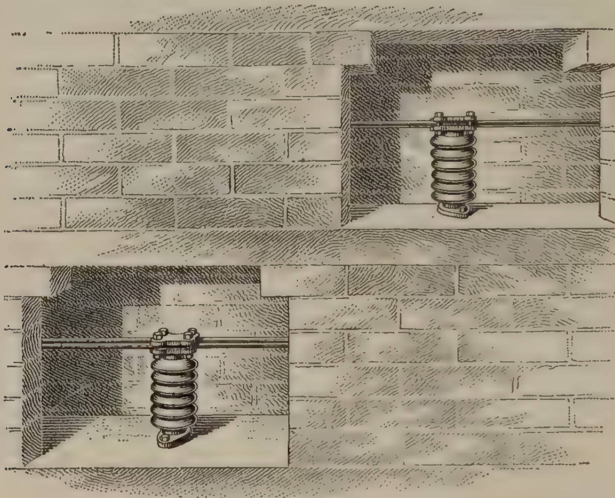


FIG. 45

advantage of separating the bus-bars in this manner is that it prevents the spreading of trouble due to a breakdown to ground and so confines the accompanying arc that it cannot reach the other bars. This form of cellular and barrier construction is not generally considered necessary on systems of voltages higher than 33,000, because at such potentials the current is limited and the arcs are not so destructive.

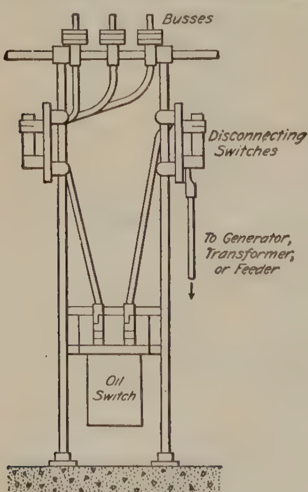


FIG. 46

73. Disconnecting switches, Fig. 22, are usually provided for opening the circuits between each oil switch and the busses, so that any oil switch can be isolated for cleaning and repair. In some cases, provision must be made for disconnecting the oil switch from the feeders as well as from the

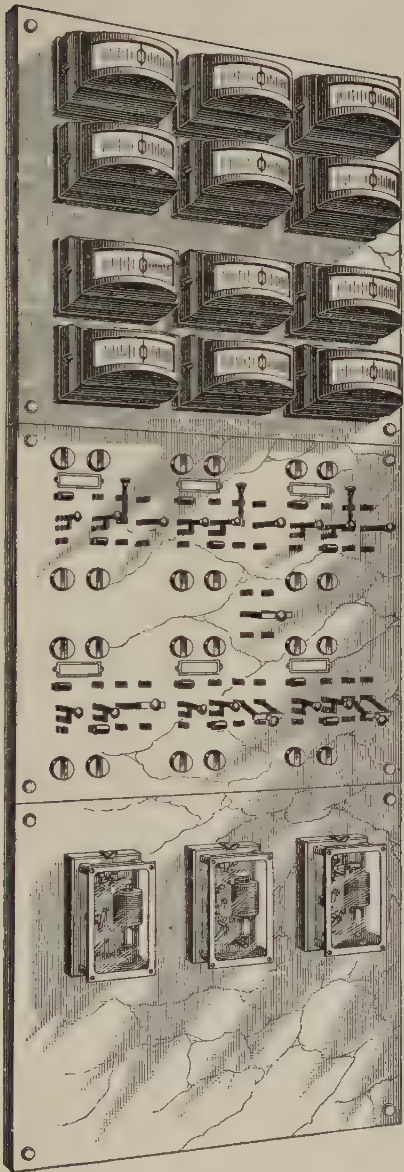


FIG. 47

busses, as shown in Fig. 46. In high-tension systems the disconnecting switches are mounted on the outside of the walls enclosing the busses, and arc deflectors, or barriers, are often placed between adjacent switches.

74. Control-Board Panels.—Switchboards for electric-control systems are usually equipped with the control switches for operating the main switches; with signal lamps for showing whether the switch is open or closed and whether the operation of the mechanism is complete; and with indicating and measuring instruments for the circuits.

A *wall-type control-board panel* for a 4,000-volt system is shown in Fig. 47.

A form of control board especially suitable for large stations is the *bench board*, or *desk board*, shown in Fig. 48. By this form of construction the control switches are placed where they can be easily reached but cannot be knocked against by persons passing them, and the switches are so placed that all of them can be reached conveniently.

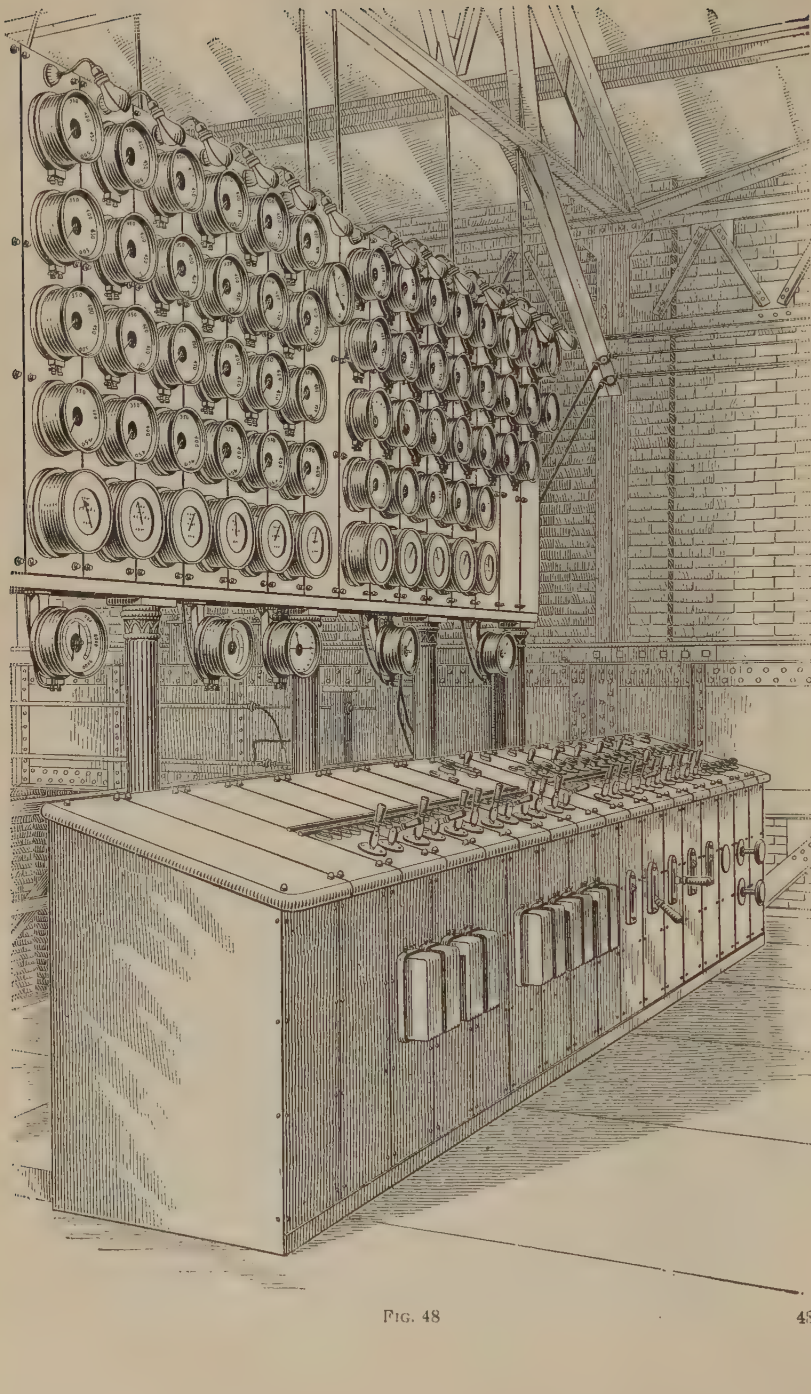


Fig. 48

ELECTRIC STATIONS

Serial 1646 — Edition 1

INTRODUCTION

NUMBER AND CAPACITIES OF UNITS

1. Location and Capacity of Station.—The location of the station is primarily one of the problems of distribution, but it is not always possible, or even desirable, to secure a station site near the load center, and it is sometimes necessary to adapt the distribution system, in some degree at least, to the location of the generating station.

The total capacity of the apparatus installed in the electric central station is determined after a careful study of the load, both existing and prospective, after which provision is made for the installation of machinery of sufficient capacity to meet the present load requirements with allowances for reasonable growth.

2. Number of Station Units.—The number of units advisable depends on the total capacity required, on the nature of the load, and on the relative importance of low first cost and low operating cost.

It is generally considered poor practice to install a plant of one generating unit. In some cases, considerations of expense have made this necessary; but, ordinarily, such an installation is undesirable, for the reason that any serious disability of one unit shuts down the entire plant. If two units are installed, each with a capacity of one-half the maximum load, the disability of one machine reduces the total capacity by only

one-half; by safe overloading during short *peaks* (high loads) from 65 to 75 per cent. of the load may be carried by one unit. If three units are installed, each having a capacity equal to one-third of the load, the disability of only one may permit nearly, or, in some cases, all of the load to be carried through a short peak.

3. Economy of operation also requires a careful consideration of the probable daily load. Generating units, especially those driven by steam, are much more efficient when running at approximately full load than when lightly loaded; therefore, an attempt is generally made to install machines of such capacity that it will not be necessary to operate any of them very lightly loaded for any considerable time. On the other hand, small units are generally less efficient than large ones, so that it is not desirable to subdivide the capacity too far.

4. The foregoing considerations indicate the advisability of installing at least three machines. The importance of the service, however, may be such as not to warrant the increased expense of installing so many units, for one large generator is nearly always less expensive than two or three smaller ones aggregating the same capacity. The importance of security of service and the possible increase or decrease in operating economy, when using several machines, must be compared with the possible decrease or increase in economy and reduction of investment when using a lesser number of generators.

5. Similarity of Units.—It is desirable to have the units similar in size, design, and construction, in order to reduce the number and cost of spare and emergency parts that should be kept on hand. Interchangeability of parts is an important item in the design of a mechanical plant of almost any kind.

If the generating units to be used in any one kind of service are not alike in manufacture, it is important that they be sufficiently similar in electric characteristics as to give the same voltage regulation, and, if they will be required to operate in parallel, they must be sufficiently alike to permit parallel operation. Alternating-current generators, to operate in parallel, must have the same frequency and the prime movers have

similar speed-regulating characteristics. If the alternators are to be belt driven, the necessary speed regulation can be secured by proper selection of pulleys. If the prime movers of alternators do not have similar speed-regulation characteristics, the generators will not operate in parallel, although, in some favorable cases, they can be connected together for brief periods for a transfer of load.

CONDUCTORS AND CURRENT DENSITIES

6. The electric conductors in a station must be of sufficient current-carrying capacity to prevent overheating. In the distribution system, the size of a conductor is generally determined by the allowable potential drop; inside the station, where distances are short, this consideration enters in a much less degree, for there the more important feature is the temperature rise of the conductors and its possible effect in detempering the spring parts of switches, overheating contacts at the joints, and causing expansion that may set up mechanical stresses in rigidly connected pieces.

Aluminum has, in some isolated cases, been used for electric conductors in stations, especially for the larger parts, such as busses, machine leads, etc., but its excessive expansion when heated and the difficulty of making good electric contacts on it have been factors in preventing its coming into common use for this purpose. Copper, on account of its high conductivity, and the ease with which it may be surfaced and soldered, is the metal most generally used in general electric construction.

7. For heavy bus-work, flat bars are in most general use; for small alternating currents, small, flat bars, or round, solid bars are suitable. If heavy alternating currents are to be carried, the skin effect may be so great as to make the use of tubular conductors preferable.

For machine leads and other similar work, stranded cable with a suitable insulating and protecting covering has been a favorite form of material. The reason is that it can be bought in one piece in any length that is likely to be needed in a station, and that it is already insulated and requires no elaborate form

of support in installation, as it can be laid in a cable trench or supported on brackets along a wall. Though more expensive to purchase than flat bar copper, cable is cheaper to install, and for low-tension work—that is, 600 volts and lower—the cost of the two, when installed, is about equal. Modern practice, in large installations of low-tension conductors, is tending toward the use of bare bar copper supported between suitable insulating materials with proper provision for avoiding short circuits.

8. In station construction providing good facilities for keeping conductors cool, a current density of 1,000 amperes per square inch of cross-section is allowable for copper conductors. Such a density will not cause serious overheating unless the conductors are unfavorably situated with reference to other apparatus liberating heat. In special cases, the current density is allowed to go as high as 1,250 or 1,400 amperes per square inch of cross-section without serious result.

DIRECT-CURRENT GENERATING STATIONS

RAILWAY STATIONS

GENERATOR CONNECTIONS

9. Circuit Diagram.—Generators for supplying current for railway service are nearly always compound wound and are connected with one terminal—usually the negative—grounded through the track system of the railway. The electric connections for two railway generators with series-field windings and equalizing connections on the negative side of the machines are shown in Fig. 1, in which *a* is a generator armature; *b*, a shunt-field winding; *c*, a series-field winding; *d*, a series-field shunt; *e*, the equalizer bus; *f*, the equalizer switch; *g*, a positive main-generator switch; g_1, a negative main-generator, or armature switch; *h*, a shunt-field rheostat; *i* and *j*, the series and shunt coils, respectively, of a watt-hour meter; *k*, an ammeter;

l, a circuit-breaker; *m*, the station voltmeter; *n* and *o*, voltmeter plug receptacles; *p*, the pressure bus, or common connection for the station voltmeter; *q*, an ammeter shunt.

Electrically, there is little difference whether the generators are compounded and equalized on the positive side or on the negative, as operation and performance are the same in either case. However, when equalizer switches are on the machine

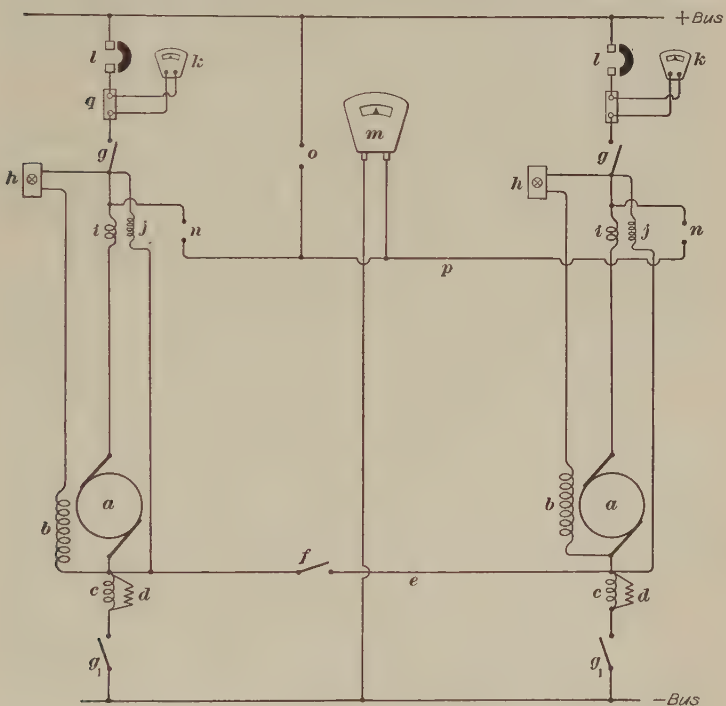


FIG. 1

frame, or on a pedestal near by, the equalizing and compounding are preferably done on the negative, or grounded, side, as station attendants are then in less danger from personal contact with the live parts of the switches.

10. Generator Panel.—The front of a typical direct-current, railway, generator panel is shown in Fig. 2, which is

lettered to correspond to Fig. 1 wherever the same devices appear in both illustrations. The hand wheel h_1, Fig. 2, operates the contact-arm of the rheostat h, Fig. 1. The double-throw, single-pole, switch s, Fig. 2, controls the station lamps; its connections are not shown in Fig. 1, because the lamps are not an essential part of the railway circuits. A glass case t, Fig. 2, protects the watt-hour meter. The type of panel shown in Fig. 2 has no negative main switch, as the usual practice is to mount this switch on the machine frame. A field switch is shown at u.

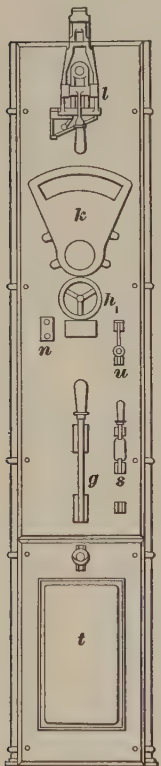


Fig. 2

11. Equalizing Connections.—The function of the equalizing connection is to distribute the current output of the generators among the series-field windings in such a manner that the generators may all compound alike; therefore, the equalizer connection must always be made to the generator between the series-field winding and the collecting ring, or bus-ring, that is connected to the brush-holder studs. The equalizer connection must be of large cross-section and as short as possible, so that its resistance will be low. Resistance in equalizer connections tends toward the prevention of proper distribution of current among the series-field windings, in which case unequal compounding and unsatisfactory division of load among generators will probably result. Equalizing switches are, therefore, generally situated near the machines, either on small panels mounted on the side of the machine frames or on pedestals set close beside the machines. The equalizer bus, which is usually at practically ground potential, is run by the shortest path from one generator to another.

12. Adjustment for Proper Division of Load.—In order that two compound-wound generators operating in parallel may properly divide the load between them, the

potential drops in the series-field circuits between the equalizer connection and the bus-bar must be equal. If the resistance in the series-field circuit of one machine is too large, the series-field winding of that machine will receive less than the proper current. As a result, the compounding of that machine will be less than it should be; if the resistance is too low, the compounding will be too large.

Neither an adjustment of the series-field shunt nor a reduction of the resistance in the equalizing bus is effective in properly distributing the output current between the series-field windings when the relative resistances of the parallel paths between equalizer and main bus are not correct. The adjustment of resistance of these parallel paths is made either by increasing resistance of one of the leads or by decreasing that of the other. The increase of resistance is effected by inserting in the lead (in series) a short length of conductor of relatively smaller cross-section, care being taken not to reduce the size of the conductor to such an extent that dangerous heating would occur; sometimes the insertion of a German silver or an iron washer under a clamping nut at a joint is sufficient. Decreasing the resistance is done by inserting additional copper in parallel with the lead already installed.

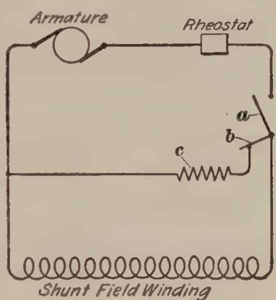


FIG. 3

13. Shunt-Field Connections.—As shown in Fig. 1, the wiring of the generator is such that the shunt-field circuit cannot be opened by the use of any of the switchgear. This is a common and desirable form of connection for it makes impossible a destructive short circuit through the armature that would result if, by any mistake, an operator should open the shunt-field circuit of the generator while it is operating in parallel with other sources of direct current.

Some engineers, however, consider provision for opening the shunt-field circuit desirable. Then a special form of field switch and a field-discharge resistance are connected as shown

in Fig. 3. The field switch consists essentially of a main blade *a* and an auxiliary blade *b* rigidly held at an angle to each other and turning together on the same hinge. Just before the main blade leaves its clip, the auxiliary blade makes a contact that short-circuits the shunt field through the discharge resistance *c*. The purpose of the field-discharge resistance is to afford a path through which the stored energy in the field may be discharged. The high electromotive force that would otherwise be generated by self-induction when the field circuit is opened may thus be avoided. In Fig. 2 the field switch is shown at *u*.

INSTRUMENT EQUIPMENT

14. The instrument equipment of the usual railway-generating station consists of a station voltmeter, an ammeter for each generator, and, generally, when there is more than one generator, a totalizing ammeter connected in the bus-bar between the generator panels and the feeder panels to show the total current output of the station.

15. **Ammeters** are of the shunt type and in some cases all or a part of the copper run between the machine terminals and the switchboard is used for the ammeter shunt, but it is more general practice to use the regular form of alloy shunt installed on the back of the switchboard between the knife-blade switch and the circuit-breaker.

16. Individual **integrating wattmeters,** or **watt-hour meters,** for each machine are sometimes installed on the generator panels and connected in the positive lead of the generator between the machine terminal and the knife-blade switch. Although somewhat more subject to accidental damage than if it were higher, the watt-hour meter is preferably placed near the bottom of the panel because it is there favorably situated with reference to electric contacts, vibration, or presence of stray magnetic fields. When the generator is shut down, both the series and shunt circuits of the wattmeter are either dead or at earth potential. The positive end of the potential circuit of the wattmeter is connected to the positive

lead of the generator at the armature switch. The negative terminal of the potential circuit may go directly to the negative pressure bus of small size (No. 12 B. & S. wire) in the rear of a switchboard, or it may be run back to the generator and connected to the negative lead of the machine, as shown in Fig. 1.

17. The **station voltmeter** is wired so that it may be connected to the main busses, or to the leads of any generator. The change of connection is made by means of a plug that fits into a receptacle, one of the contacts of which connects to the voltmeter and the other to the leads of the generator, as *n*, Fig. 1, or to the main bus, as at *o*. There is a separate receptacle on each generator panel, and, in order to observe the voltage of the generator, the plug is inserted in the receptacle on the panel of that particular machine. The positive voltmeter connection to the generator leads is made on the machine side of the knife-blade switch, because then the generator voltage can be observed before the switch is closed. The station voltmeter is usually supported on a bracket that can be swung out from the switchboard to such a position that the instrument can be observed from any panel; it therefore does not show on the panel, Fig. 2.

SWITCHES AND CIRCUIT-BREAKERS

18. The **main positive armature switch** *g*, Figs. 1 and 2, is so situated that its handle will be about as high as the waist or chest of a man of ordinary size, a position in which it can be most easily and conveniently operated.

19. The **circuit-breaker** *l*, Figs. 1 and 2, is situated at the extreme top of the generator switchboard panel. The space for a distance of about 4 feet above the circuit-breaker is kept clear of any grounded metal work, switchboard instruments, switchboard framework, or anything else that might be injured by the arcs. In order to protect the switchboard panel from the destructive effect of arcs, the circuit-breakers, especially in the larger sizes, have a fireproof shield of thin fibroid on each side, also, in the rear of the contacts and between

them and the switchboard panel and also projecting above the panel in such position as to prevent the arc from burning the switchboard or communicating to the supporting steel framework. The circuit-breaker is operated on the occurrence of overload or low voltage, by means of tripping devices. As the pressure of the circuit is much higher than the 60 to 100 volts ordinarily required for energizing the low-voltage release coil, it is necessary to secure the lower voltage drop through the solenoid by inserting an external resistance, not shown in Fig. 1. This is mounted in the rear of the switchboard panel near the circuit-breaker. The supply for the low-voltage release coil is taken from between the knife-blade switch and the circuit-breaker, so that when switch *g*, Fig. 1, is open, it is necessary to close the circuit-breaker, in order to obtain current for the release coil.

In some cases, an alarm bell is provided to ring when the circuit-breaker is open. The alarm-bell circuit is closed by a plunger that is thrown out when the circuit-breaker opens. In order that the bell may not ring when the breaker is intentionally left open, a small switch is placed in the alarm circuit.

FEEDER CONNECTIONS

20. Direct-Current, Railway, Feeder Panel.—The switchboard of a direct-current, railway station has two main divisions, generator panels and feeder panels. The latter bear the switchgear necessary for the feeders that carry current from the positive bus—which extends the entire length of the switchboard and which receives current from the generators, as shown in Fig. 1—to various sections of the railway line.

The connections of a typical railway feeder panel are shown in Fig. 4. The feeder connection to the bus is made through a short length of copper that connects to the upper terminal of the feeder circuit-breaker *a* situated near the top of the panel.

The knife-blade switch *b* is situated on about the same level as the knife-blade switches on the generator panels. The switch may either be arranged with a quick-break connection or without it. The most recent practice has been to omit

the quick-break feature; the feeder circuit can be quickly opened by tripping the low-voltage release on the circuit-breaker. The knife-blade switch then becomes merely a disconnective device and is not much used for interrupting the current.

The ammeter shunt *c* is connected in the lead between the circuit-breaker and the knife-blade switch, as is also the choke coil *d*. The lightning arrester *e* is connected on the feeder side of the knife-blade switch, and, in some installations, is mounted on the rear of the panel near the floor; in other installations, the arresters are isolated from the switchboard.

The voltmeter plug receptacle *f* is connected between the pressure bus and the feeder side of the knife-blade switch to allow of the trolley voltage being read before closing the switch in cases where feeders are interconnected or continued to other sources of power.

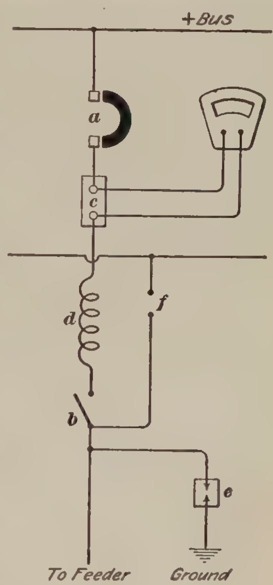


FIG. 4

21. Auxiliary Bus.—Circuit-breakers on railway feeders are required to open under heavy overloads and short circuits and are subject to severe service. This results in an occasional burning of the contact parts and the necessity of making minor repairs at more or less frequent intervals. In order to provide for taking circuit-breakers and ammeters out of service for such repair work without interrupting the output on its feeder, the knife-blade switches are sometimes made double throw, their lower clip being connected to an auxiliary bus that is joined to the main distributing bus through a circuit-breaker and a knife-blade switch. This connection also has an ammeter, and the auxiliary bus connection can be used by simply closing its circuit-breaker and knife-blade switch and throwing the knife-blade switch of the feeder down to the auxiliary switch clip.

22. Booster Feeders.—Sometimes the very long feeders have low voltages at the ends distant from the station, although the pressure on the remainder of the system may be fairly good. Too high bus-pressure is objectionable, because motors near the station may then be burned out or otherwise damaged. In such cases, boosters are sometimes connected in series with the long feeders that require a voltage somewhat higher than that of the main bus. The booster, itself, is an auxiliary motor-driven generator and the voltage it generates is added to the voltage of the main generators.

The booster generator may be either shunt or compound wound, but is more generally compounded to provide for the extra length of the feeder, the machine generators being compounded only for a moderate length of feeder, and the booster generator for the additional length.

23. Leading Out Feeder Cables.—The method of leading out the feeder cables is generally dependent on the type of line construction used. If the distribution system is placed underground, the cables are led out of the station building through conduits or ducts leading in through the basement wall. There is a possibility of a breakdown of the insulation between the conductor and the grounded lead cable sheath of underground distributing cables with resulting arcs. For this reason, it is undesirable to group closely together a large number of cables without some fire-resisting cover around them for protection against the destructive effects of such arcs. Installations of underground cable, therefore, should be covered with conduit or cement up to the point where they are separated sufficiently to remove the danger of injury from an arc or burn on an adjacent cable. When they are installed on cable racks in such fashion that the cables are separated by about 6 or 8 inches, there is little danger from this source; but in order to lessen the danger, the lead cable sheath is generally discontinued at the point where the cables enter the cable rack.

ARRANGEMENT OF SWITCHBOARD PANELS

24. If one ammeter (totalizing ammeter) is to show the total output of the station, all the generator switchboard panels are placed at one end of the board and the feeder panels at

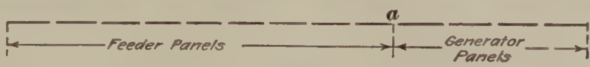


FIG. 5

the other, as indicated in Fig. 5. The shunt for the totalizing ammeter is then installed at a, so that the instrument indicates all the current output of the station. In many cases, where it is desirable to lead feeder cables out of the station by two routes and, at the same time, have a systematic arrangement of switchboard panels and outgoing feeders, generator panels are installed in the central portion of the switchboard and feeder panels on each side of them as indicated in Fig. 6. By this arrangement, the operator is obliged to observe two ammeters

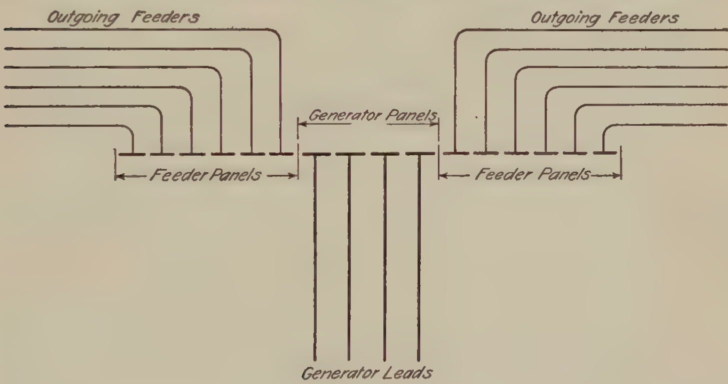


FIG. 6

in order to determine the total output of the station, but this is not usually an inconvenience serious enough to interfere with the most consistent and suitable layout of feeder panels.

DIRECT-CURRENT, LIGHT AND POWER STATIONS

CLASSIFICATION

25. Generating stations for distributing direct current for light and power are of two general kinds: Those using shunt-wound generators and those using compound-wound generators. Compound-wound generators will not operate satisfactorily in parallel with storage batteries, and therefore shunt-wound generators are used in stations employing batteries either for assisting in pressure regulation or for emergency or peak-load service. If no storage batteries are used, compound-wound generators, on account of their superior voltage regulation, are generally employed, especially if the load is fluctuating. Shunt-wound machines require much more frequent attendance with fluctuating loads than do those that are compound wound.

SMALL, TWO-WIRE PLANTS

26. Generator Connections.—Small, direct-current, light and power stations are not usually provided with storage batteries and therefore generally have compound-wound generators. The amount of compounding is adjusted to regulate the voltage for some representative point in the distributing system, so that the best average result in pressure throughout the system will be obtained.

Fig. 7 shows a wiring diagram of two compound-wound generators connected to a two-wire, direct-current system. In this installation, neither of the machine terminals are grounded and both of the machine leads are brought to the switchboard and led through knife-blade switches *a* and circuit-breakers *b* to the busses. With reference to the kind of protective device preferable for such installations, engineers are at variance; some favor fuses on account of their lesser expense, while others prefer circuit-breakers because of their more reliable operation; each form is in quite general use. One circuit-breaker for each machine is the usual practice for the protection of generators

on two-wire systems; when fuses are used, one is generally installed in each generator lead—two for each machine.

27. The wiring diagram shows an equalizer connection *c* that is necessary when two or more compound-wound machines are installed, but unnecessary if there is only one unit. When two generators are to operate in parallel, one equalizer switch *d* is necessary; with more than two generators in parallel one equalizer switch is installed for each machine. In this diagram, the compounding and equalizer connections are shown on the

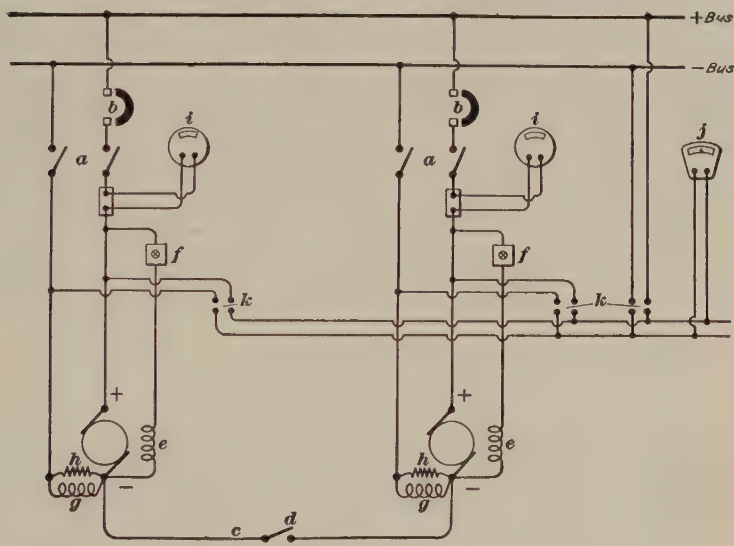


FIG. 7

negative side of the generator; they can be on either side, if the system is ungrounded, but the connections should not be on the same side as the circuit-breaker.

Both polarities of the machine have their armature switches *a* on the switchboard, so that the generators can be entirely separated from the conductors of the distributing system.

The installation shown in the wiring diagram has a short shunt; that is, the shunt field *e* is connected on the armature side of the series-field winding, which gives fewer joints at which the shunt-field circuit could be accidentally opened. So

far as the performance of the machine is concerned, it is immaterial whether a long or short shunt is used. Each shunt-field circuit contains the usual rheostat *f*, and each series field *g* is usually provided with an adjustable shunt *h*.

28. Instrument Equipment.—The instruments for a small direct-current station usually include an ammeter *i*, Fig. 7, for each unit and one station voltmeter *j* with a multiple-point voltmeter switch (plug and receptacles *k*) by which the instrument connection can be switched to the busses, or either set of machine leads. In some cases, pressure wires are run back from the feeder ends at the distributing centers and terminate at the multiple-point voltmeter switch, so that it is possible for the operator to observe the pressure at important feeding centers. This, however, is rather uncommon in the smaller stations and is done only when pressure regulation is of extreme importance. In some installations, a totalizing wattmeter is installed between the generator panels and feeder panels, and sometimes individual watthour meters are installed on the leads of each generator unit.

SMALL, THREE-WIRE SYSTEMS

29. Three-Wire System With Two Compound Generators.—The simplest method of supplying a three-wire system consists in the use of two generators, each supplying from 110 to 125 volts, connected in series between the two outside conductors, and with a common connection to the neutral, as shown in Fig. 8 (*a*), in which the various parts will be recognized from a knowledge of preceding diagrams. The connections shown in Fig. 8 (*b*) differ from those in (*a*) only in the arrangement of the neutral leads and switches. This is the oldest form of three-wire system, and is still used to some extent where the unbalanced load is large.

For parallel operation, two equalizer busses are necessary; one for machines connected to the negative main bus, and the other for those connected to the positive main bus. With an ungrounded system, it is immaterial on which side the machines

are compounded and equalized. However, when the neutral of the three-wire system is grounded, as is frequently done, equalizing and compounding the neutral side of each generator results in putting the equalizing switch at practically ground

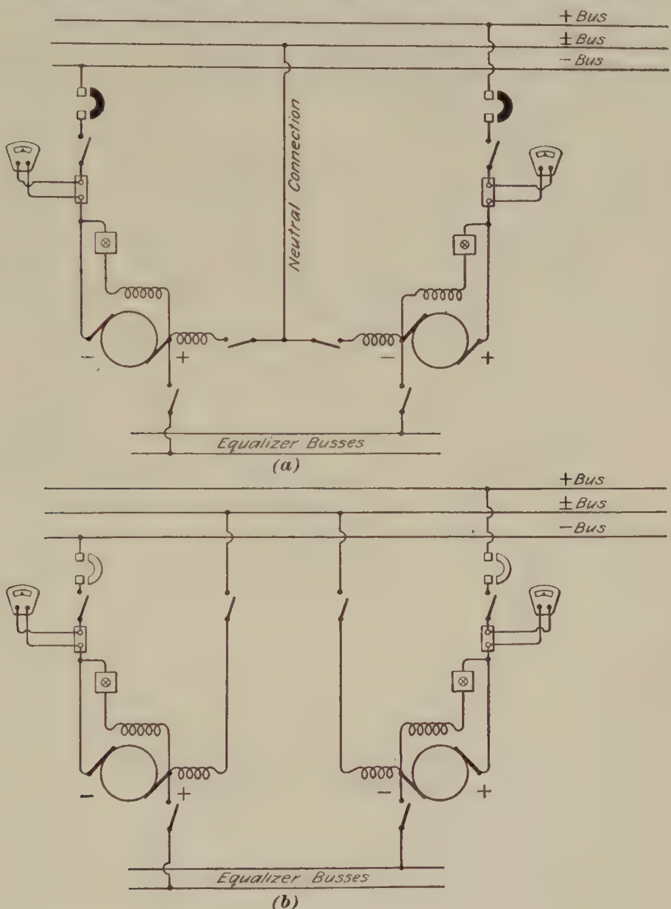


FIG. 8

potential, and thus confines to the switchboard those switches which are not at earth potential.

The instrument equipment for such an installation does not differ from that of the two-wire station, except that a voltmeter

is required on each side of the system. The voltmeter connections are not shown in Fig. 8.

30. Derived Neutral With Balancer Set.—On account of the expense of providing two generators for use on three-wire systems where one of twice the capacity would be cheaper and sufficient for carrying the load, various forms of derived neutrals have been resorted to.

One device for providing for unbalanced loads, and one that automatically adjusts itself to considerable changes of load, is an **equalizer, or balancer, set**, consisting of two small

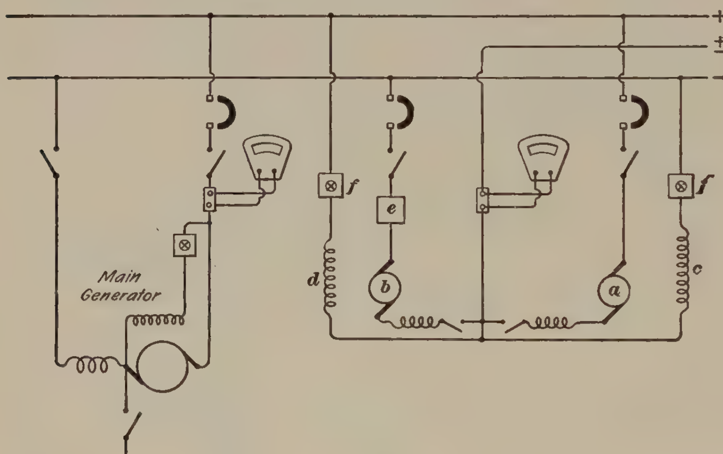


FIG. 9

dynamo units *a* and *b*, Fig. 9, exactly alike, mounted on the same shaft or, in some cases, belted to each other. The balancer units may be either shunt or compound wound, according to whether they are used in parallel with shunt- or compound-wound generators. The machine *a* connected between neutral and positive conductors (referred to as the *positive machine*) has its shunt field *c* connected between the neutral and negative conductors of the system, while the current for the shunt field *d* of the negative machine *b* is taken from the neutral and positive conductors. The result is that when the voltage of either side becomes high, the armature of the machine connected

to that side is supplied with a relatively high potential, but its field winding, being supplied from the low-pressure side of the system, is made weak, a condition that causes the machine to speed up as a motor. The other machine, under the reverse condition, has no tendency to speed up, but is driven as a generator by the motorized machine, and so constitutes an addition to the generating capacity on the lower voltage side. Thus the balancer acts as a medium of transfer of generating capacity from the lightly loaded to the heavily loaded side of the three-wire system.

The balancer set is started with one of the machines operating as a direct-current motor, the other acting as a generator on open circuit. When up to speed and voltage, the generator end is paralleled to one side of the system. The machine that starts as a motor is provided with a suitable starting box *e*, Fig. 9. Field rheostats *f* are used in connection with the balancer to regulate the speed and to provide for unbalancing the bus pressure, if such unbalancing becomes necessary, in order to obtain the proper pressure at the feeding centers.

31. If the main generator supplying the load is provided with circuit-breakers, the balancer set should also be supplied with a circuit-breaker in series with each machine and made electrically or mechanically interlocking with the one on the main generator so that when the main generator circuit is opened the balancer circuit also will be opened. This results in shutting down the balancer set, but is necessary because the balancer armatures must be disconnected before the bus is again energized; otherwise, the balancer will be severely damaged. Instead of mechanically or electrically interlocking circuit-breakers, the balancer set is sometimes provided with those having low voltage release coils, so that the opening of the circuit-breaker on one generator, while other generators remain connected to the bus, will not disconnect the balancer set unless the bus is killed, or deenergized. The ammeter in the neutral must have a two-way scale, with the zero mark in the center.

32. Derived Neutral With Three-Wire Generator. The essential features of one scheme of wiring for a three-wire generator are shown in Fig. 10. The generator has two series-field windings *a*, and therefore two equalizing busses are necessary for parallel operation. In order that the full output on either side of the machine may act on the protective devices, the fuses or circuit-breakers *b* are installed, as shown, in the circuits between the brushes and the equalizer busses. If the circuit-breakers were between the series fields and the main bus-bars and two or more generators were operating in parallel, the current tending to open a breaker might be either greater or less than the actual output of the machine, and the protective action would be unreliable. Owing to the current in the equalizer connection, the currents in the series field and the armature are not always the same.

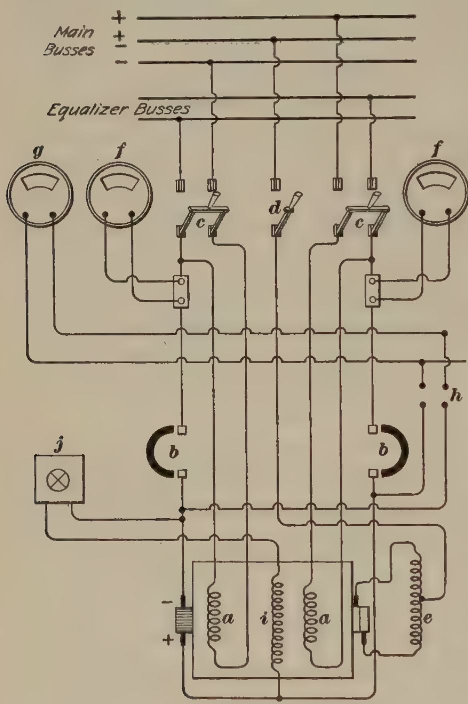


Fig. 10

33. By the arrangement shown in Fig. 10, the equalizers are at the pressure of the outside main busses (except for the drop through the series-field windings), and the pressure of the machine must be fully built up before it is connected in parallel with a generator already running. For this reason the switching equipment is such that the series fields of the two machines can be energized before the armatures are connected, the

sequence of switching operations being as follows: Start with all switches and breakers open; throw in the series fields by closing the two double-pole main switches *c*; when the machine voltage is properly adjusted, close the circuit-breakers, one at a time (one pole at a time, if a double-pole breaker is used); close the neutral switch *d*.

34. The compensator winding *e*, Fig. 10, is of rather small capacity and is intended to carry only the difference between the currents on the two outside conductors, which, in a well-balanced system, is comparatively small. In order that the opening of the circuit-breaker on one side of the system may not throw the entire load of the other side of the machine onto the compensator, the positive and negative circuit-breakers of each machine are mechanically or electrically locked together, so that the opening of one necessarily opens the other also.

With a three-wire generator, it is the usual practice to use two ammeters *f*, Fig. 10, and, like the circuit-breakers, they must be connected between the armature and equalizer, in order that, when two or more generators are operating in parallel, they may measure only the actual current output from each. The station voltmeter *g* is connected to the usual pressure busses and can be made to indicate the machine voltage by inserting the plug into the receptacle *h*.

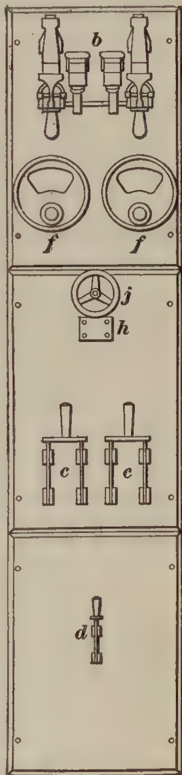


FIG. 11

35. If a three-wire generator is provided with either fuses or circuit-breakers, the shunt field *i*, Fig. 10, must be connected on the armature side of them, in order to avoid the opening of the shunt-field circuit when the protective devices act. If the field connections were such that the protective devices were to open the shunt-field circuit, there would be induced in the field winding a very high electromotive force, which might be

sufficient to puncture the insulation. The usual shunt-field rheostat *j* is provided.

A three-wire generator panel for a small, direct-current plant is shown in Fig. 11, which is lettered to correspond with Fig. 10, except that in Fig. 11, the letter *j* represents the shunt-field rheostat handle instead of the rheostat itself.

BUSSES AND FEEDERS OF SMALL, DIRECT-CURRENT PLANTS

36. The bus-bars of the switchboard of small, direct-current, lighting and power plants are usually mounted on insulating supports carried on brackets from the switchboard supporting framework. The connections between the busses and switches or circuit-breakers are flat copper bars bent to suitable shape and fastened in place by machine bolts.

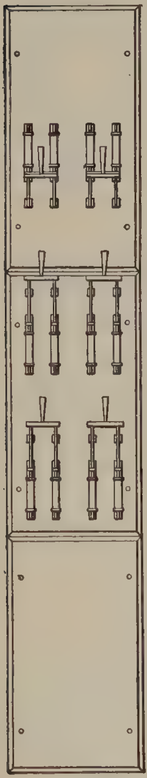


Fig. 12

The feeder switches are on the front of the board. In the two-wire system, double-pole, single-throw, feeder switches are in general use. In small plants, it is general practice to install cartridge fuses on the front of the board immediately under or over the switches, as shown in Fig. 12, which represents a six-circuit, two-wire, feeder panel.

In stations connected with three-wire systems, all three busses are generally mounted in the rear of the switchboard panels. However, in some systems with grounded neutrals, the neutral bus is mounted on the wall near the point where the feeders leave the building, and the neutral conductors of the feeders start from this point.

On ungrounded three-wire systems, it is the more common practice to install the positive, negative, and neutral switches and fuses on the feeder switchboard. Sometimes, the neutral conductor is protected by a fuse as heavy as that in either of the outside conductors, and, sometimes, with a fuse of only one-half the size of the positive or

negative fuses. There is considerable difference in opinion as to the proper size of neutral fuses and both forms of practice are common.

In small stations, circuit-breakers on the feeders are not very common, unless the kind of service is such as to cause frequent overloads. The practice of installing ammeters on feeder circuits does not generally prevail in small plants of the type that are being considered.

MEDIUM-SIZE, DIRECT-CURRENT, LIGHTING AND POWER PLANTS

37. Generator Connections.—Medium-size, direct-current, lighting and power plants, especially if feeding a territory of moderate extent, are generally connected to three-wire systems.

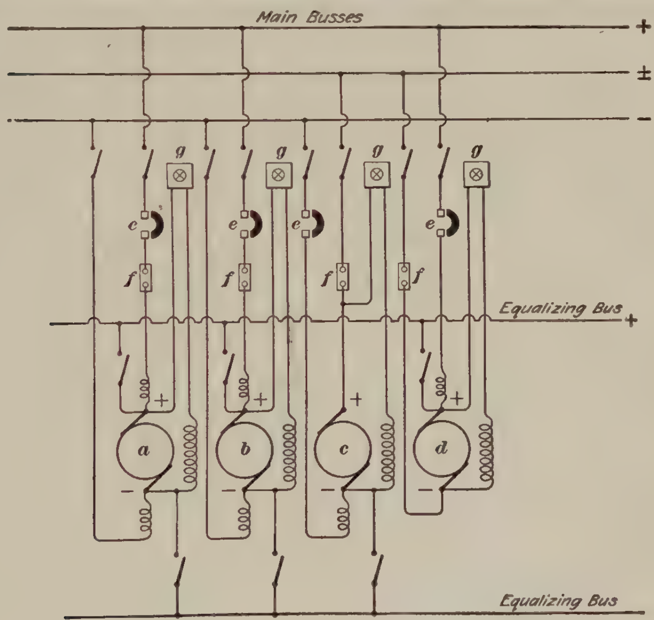


Fig. 13

Fig. 13 shows the connections of a station in which most of the energy is generated by 220- to 250-volt machines *a* and *b* connected to the positive and negative (outside) conductors

of the system; smaller 110- to 125-volt series-connected generators *c* and *d* take care of the unbalance in load. Such a station, generally, has two sets of the lower voltage units, one operating while the other is shut down for maintenance or repair work; all the other units are 220- to 250-volt generators, on account of the smaller cost per unit of power for the larger machines.

Circuit-breakers, ammeter shunts, and shunt-field rheostats are indicated at *e*, *f*, and *g*, respectively, in Fig. 13; the switchboard is also provided with the usual station voltmeter and plug receptacles.

38. Busses and Feeders.—On account of the larger territory covered and the greater length of feeders, as compared with a small plant, there is some difficulty in keeping a good average pressure over the entire system of a medium-size plant. Those feeders that terminate near the station should therefore either be supplied with a lower voltage than that furnished to distant feeding centers or should have smaller cross-sectional areas than the long feeders to make a uniform fall of potential throughout the system. The latter alternative is uneconomical and, besides, introduces a risk of seriously overheating some of the conductors. If short feeders carrying large currents are installed, care should be taken to check the safe current-carrying capacity of the feeder with the full-load current that is transmitted.

The more general and preferable practice is to provide two separate sets of busses supplied by generators of different voltages. The generators and feeders are provided with double-throw switches to make the switching selective between the two different busses, which are kept at pressures suited to the requirements. In some cases, the entire supply is delivered to one bus from which another bus of higher potential is supplied through a series-booster generator that increases the pressure by a desired amount.

The instrument equipment of feeder panels in the medium-size plants is usually somewhat more complete than that in the smaller stations and includes an ammeter for each feeder.

LARGE, DIRECT-CURRENT, CENTRAL STATIONS

39. Generator Connections.—Direct-current, central, generating stations in large cities usually have storage batteries in parallel with the generators. In such stations, shunt-wound generators are employed, because the voltage characteristics of compound-wound machines render them unsuitable for operation in parallel with storage batteries. Some large stations use compound-wound generators and no batteries, and these differ from the medium-size plants chiefly in size and not materially in the system of connections.

Like the medium-size plants, large direct-current stations for lighting generally supply three-wire distribution systems. Most of the modern installations have three-wire generators.

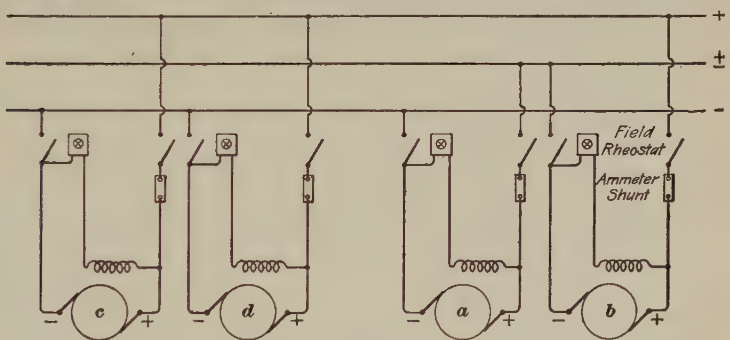


FIG. 14

Others have one or two sets of 110- to 125-volt generators, *a* and *b*, Fig. 14, for supplying the unbalanced load, and the remainder of the generating capacity in the form of 220- to 250-volt sets, *c* and *d*, usually direct connected (mechanically) to their prime movers. The connections of shunt-wound generators, Fig. 14, are simpler than those of compound-wound generators, as indicated in Fig. 13, neither series-field winding nor equalizer connections being required for the shunt-wound machines.

40. Neither circuit-breakers nor fuses are shown in Fig. 14. These are sometimes installed, though they are not common in large city plants, especially if several large stations feed into

one common network distributing system. To protect the small apparatus with circuit-breakers and fuses and to leave the large and more costly generators entirely without automatic protection appears inconsistent; but a shunt generator, on account of its armature characteristics, requires little protection—if a short circuit occurs, the voltage drops to zero, thus providing instant and automatic protection. In addition, if two or more large stations are feeding into one system, the operation of protective devices in one station would probably lower the system pressure, overload the other station, and automatically shut it down. If this should occur, considerable difficulty might be experienced in getting the system alive again, the trouble increasing with the number of stations supplying the network. For these reasons the modern tendency is, in large stations, to install no protective devices on the shunt generators; dependence is placed on the feature of automatic protection inherent in these machines.

41. Busses and Feeders.—In large, direct-current, lighting and power stations, generators and feeders are nearly always made selective in switching between at least two busses, in order to provide for multiple bus operation to improve the distribution; three or more busses may be installed in some stations.

In some large systems the outgoing feeders are not fused at the switchboard, on account of the danger that might result from the severe blowing of fuses and the possibility of starting an arc that might communicate to other parts of the switchboard and do serious damage. In such systems, it is common practice to install fuses at the feeder end out on the line and to open the feeder switch at the station when the feeder ammeter shows indications of a ground or short circuit outside. Then the current sent by the back feed from the network distributing system into the ground or short circuit, if the trouble is between the station and the distant feeder end, must necessarily pass through the feeder-end fuses. If the current is sufficient to blow the fuses, the faulty cable is thereby isolated from the network system.

42. Instruments.—In a large, direct-current, central station there is, of course, an ammeter on each generator panel. Also, on account of the more exacting requirements in distribution—and, therefore, in the detection of unusual conditions, especially on the network distributing system—it is a general practice to install an ammeter on both the positive and negative conductors of each feeder. These not only indicate the load on any particular feeder end, but serve to indicate the existence of trouble, as short circuits or grounds, on the feeder cable itself. In large systems where the load is growing rapidly and where the feeders are interconnected, the load that each feeder carries must be known, in order that it may not become overloaded by the growth of the business in that particular section, and feeder ammeters are therefore essential.

Correct regulation of the pressures at the different feeding centers is a matter of extreme importance, and voltmeters, one for each side of the three-wire system, are installed in the station and connected to pressure wires that come back from important feeding centers. Usually, there is selected one feeder, called a *standard feeder*, that is considered representative of the feeders connected to any particular bus; when the pressure at the end of the standard feeder is correct, all the feeders supplied from the same bus are considered to have a good average pressure condition at their ends. Usually, one standard feeder is selected for each bus in operation. The voltmeters are provided with a selective switch arrangement, such that they may be switched from the pressure wires to the bus. Recording voltmeters are sometimes installed for the purpose of giving graphic records of the pressures at the feeding centers at all hours of the day, so that the operating engineer may know how efficiently the pressure regulation throughout the system has been carried on.

ALTERNATING-CURRENT STATIONS

PARALLEL OPERATION OF ALTERNATORS

43. Alternating-current generators, designed for the same pressures, frequencies, and similar wave forms, can be operated in parallel, but with somewhat more difficulty than direct-current units. If the alternators are of unlike design and construction or if the driving power of one has different speed regulation from the prime movers of the others, this difficulty is greatly increased, and may be sufficient to make parallel operation undesirable, or even impossible.

If the polarity of one of two direct-current generators normally connected in parallel is reversed with respect to the other, that is, if the negative terminal of one is connected to the positive of the other and the positive terminal of the first to the negative of the second, the result will be a short circuit in which the voltage will be the sum of the pressures of both generators and the resistance will be the sum of the resistances of the two armatures and the conductors connecting them. A short-circuit of the same character exists when the electromotive forces of two alternators connected in parallel are 180 electrical time-degrees out of phase with each other.

As the polarity of an alternator is reversing with every alternation, if another alternator is to operate in parallel with it, the second, in order to have its instantaneous polarity the same as that of the first, must be reversing its pressure at the same time, and each of the terminals that are to be connected must be alive with positive or negative potential at the same instant. When this condition exists, the electromotive forces of the alternators are said to be in *synchronism* and *in phase* with each other.

44. For the proper paralleling of alternators, three conditions are necessary: The electromotive forces should be alike or nearly so; the machines must be running nearly in synchronism

before the paralleling connection is made; the electromotive forces must be in phase with each other at the instant that the parallel connection is made. Immediately the alternators are connected in parallel, the second requirement changes to that in which the units must be in perfect synchronism.

The reason for the first requirement is to avoid a heavy flow of cross-current between machines after paralleling; for the second, so that the incoming machine can get into phase with the running machine; and for the third, to avoid serious injury to the armatures and possibly, also, to the engines, if each generator were to short-circuit the other. Perfect synchronism, after paralleling, is necessary to prevent the generators from falling out of phase, or out of step, which would cause a short circuit.

Alternating-current generators, driven by synchronous motors, are not subject to speed control for paralleling, and the steps to be taken to get them into phase with each other are treated in another Section. The condition of parallel operation is fairly stable, for, if one tends to increase slightly in speed, it takes a larger part of the load, which pulls it back in phase; or, if no load is connected, it motorizes the other generator, thus equalizing the phase relations of the two.

45. Observations to determine the proper phase relations between alternators to be paralleled can be made by the use of synchronizing lamps, by a voltmeter connected in parallel with synchronizing lamps or a special resistance, by a voltmeter properly connected between pressure leads from the machines, and by means of the synchronizer, or synchroscope. Of these, the lamps are the least reliable and the synchronizer, or synchroscope, is the best.

SYNCHRONIZING CIRCUITS

SYNCHRONIZING WITH LAMPS

46. Synchronizing With Lamps Dark.—The most common device for indicating synchronism is a circuit containing one or more incandescent lamps properly connected between the sources of the electromotive forces that are to be tested for synchronism. The simplest case is the synchronizing

connections of a pair of low-voltage (110-volt), single-phase alternators connected to mutual busses, as in Fig. 15. The alternator *a* is assumed to be supplying energy through the switches *b* to the bus-bars. The alternator *c* is assumed to be generating an electromotive force, but with its armature switches *d* open. The circuit between the two alternators is complete through the synchronizing lamps *e*. If the electromotive forces of the two machines differ widely in phase, even though equal in value, cross-currents passing between the alternators will cause the lamps to glow. If the alternators are exactly in synchronism, the electromotive forces will at each instant, except the instant of reversal, be in opposition to each other, and, if equal in voltage, no current passes through the lamps, which then remain dark. In practice, the switches *d* are closed when the machine *c* has attained approximate synchronous speed, as indicated by the lamps *e* changing slowly from brightness to darkness; the switches are closed in the middle of a dark period, and the alternators then bring each other into exact synchronism automatically. When synchronizing machine *a* with machine *c* lamps *f* are used.

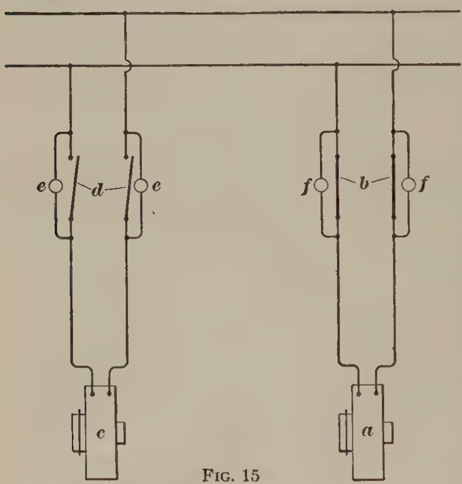


FIG. 15

47. Synchronizing With Lamps Bright.—Because there is a comparatively wide range of voltage over which lamp filaments will not glow, the absence of a glow does not accurately indicate the condition of no difference of potential between terminals of the switches *d*, Fig. 15, and, consequently, synchronizing with dark lamps is somewhat uncertain. If the

lamps are connected as shown in Fig. 16, which is lettered to correspond to Fig. 15, the electromotive force tending at any instant to send current through the lamps *e* is not the difference, but the sum, of the electromotive forces of the generators at that instant. Because a change in pressure of a few volts makes a considerable change in the brightness of a lamp that is already glowing at approximately normal brilliancy, and a like change near the zero value of the voltage produces a smaller change in brightness, many engineers consider the method of Fig. 16 the more reliable form of connection. In addition, the possibility of the lamps burning out during synchronizing operations and thus being dark and giving an indication of in phase relations when the electromotive forces are really out of phase is urged in favor of bright-lamp synchronizing connections. The operation of synchronizing with lamps bright is the same as the dark-lamp method, except that the alternator switches are closed in the middle of a period when the lamps are burning brightest.

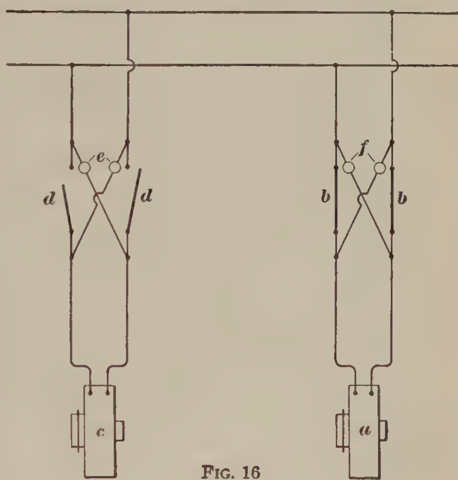


FIG. 16

48. Synchronizing-Lamp Connections for High-Voltage Single-Phase Machines.—The simple forms of connections just described are not suitable for use with high-voltage generators. By wiring enough lamps in series, synchronizing could be performed with lamp circuits connected to the generator leads, but the number of lamps required would be very large and the high voltages carried by the synchronizing circuits would be dangerous to the operator. Pressure, or potential, transformers, are always used to obtain low voltages

for the synchronizing circuits of alternators generating more than 300 volts.

In Fig. 17 are shown the connections for synchronizing high-voltage, single-phase alternators to the bus-bars. The synchronizing lamps are connected between the low-voltage winding of the potential transformer *a* and the synchronizing busses *b*. The high-voltage winding of a potential transformer *c* is connected across the leads of each alternator between the armature terminals and the armature switches; the low-voltage windings of these transformers are connected through plug receptacles *d*

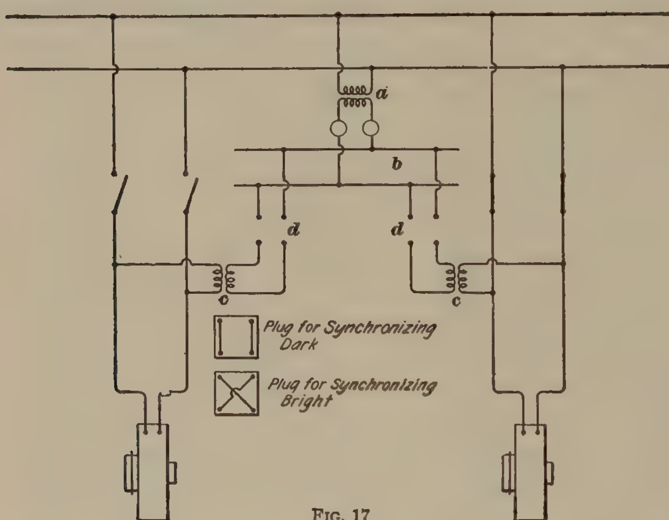


FIG. 17

to the synchronizing busses. Inserting the plug switch in the synchronizing receptacle on the panel of a generator to be started completes the connections for synchronizing that generator with the main busses. By connecting the potential transformers with proper attention to polarities or by selecting a plug switch with the proper connections, the lamps can be arranged to indicate synchronism when dark or when bright. as desired.

49. The potential transformer connected to the leads of the running generator can be used to supply a low pressure

to the synchronizing circuit, as in Fig. 18; but some engineers consider that there is some advantage in synchronizing to the bus-bars, as in Fig. 17, instead of to another machine. With more than two alternators, two plugs, or sets of synchronizing switches, are necessary when synchronizing with a machine already in operation, one plug to connect the synchronizing lamps to the potential transformer of the running machine and the other to connect them to the transformer of the starting machine. Even in large stations, however, it is not uncommon to install connections so that generators are synchronized by means of pressure transformers connected on machine leads only.

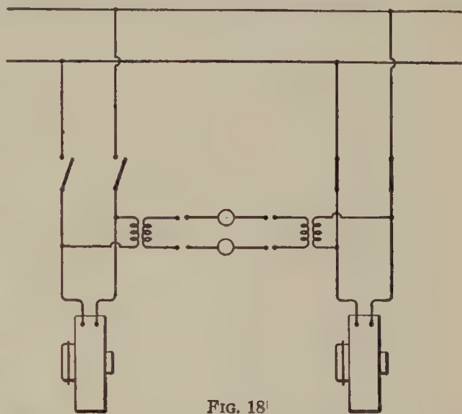


FIG. 18

50. Synchronizing Circuits for Polyphase Alternators.—If one phase of a polyphase alternator is in synchronism with one phase of another alternator, the other phases will be

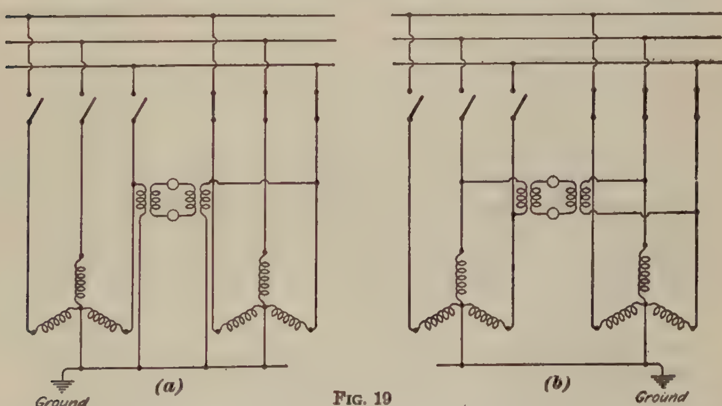


FIG. 19

in synchronism—provided, of course, that the machines are properly connected. Synchronizing circuits are, therefore, connected to only one phase of polyphase alternators. Fig. 19 shows two methods of connecting synchronizing circuits to three-phase, Y-connected generators with grounded neutrals. In (*a*), the connections are made between one phase conductor and the neutral; in (*b*), between two phase conductors. Generators with delta-connected armature windings are synchronized by means of potential transformers connected across corresponding phases of each machine, as in Fig. 20. The synchronizing connections of two-phase generators, also, are made across corresponding phases of each machine. In Figs. 19 and 20, the synchronizing plug receptacles are not shown. As with single-phase machines, the lamps can be connected to indicate synchronism, either when dark or when bright.

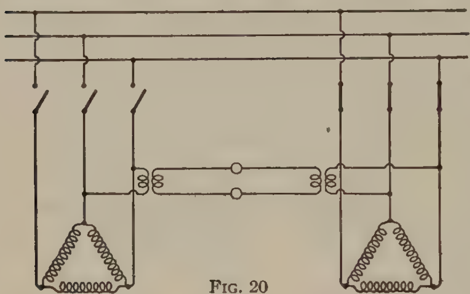


Fig. 20

Polyphase machines can also be connected so as to synchronize to the bus-bars, as shown for the single-phase machines in Fig. 17, in which the single-phase conductors can be considered as one phase of a polyphase system.

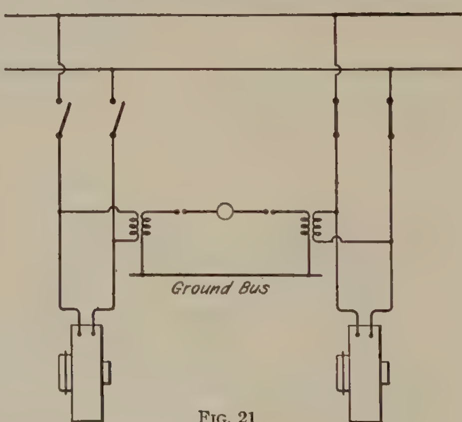


Fig. 21

51. Grounded Synchronizing Circuits.—In many installations, the secondary windings of all instrument transformers are grounded on one side to a small copper bus-bar that runs around the station and to which the

return circuits of instruments are connected. By taking advantage of the ground bus, the wiring of synchronizing circuits can be simplified considerably, as shown in Fig. 21.

SYNCHRONIZING WITH VOLTMETERS

52. **Simple Connections.**—Synchronizing lamps can be regarded as only approximately reliable. In order to obtain an indicating device that can be relied on, the station alternating-current voltmeter is sometimes connected in place of one of the lamps. The indication of the instrument at synchronism

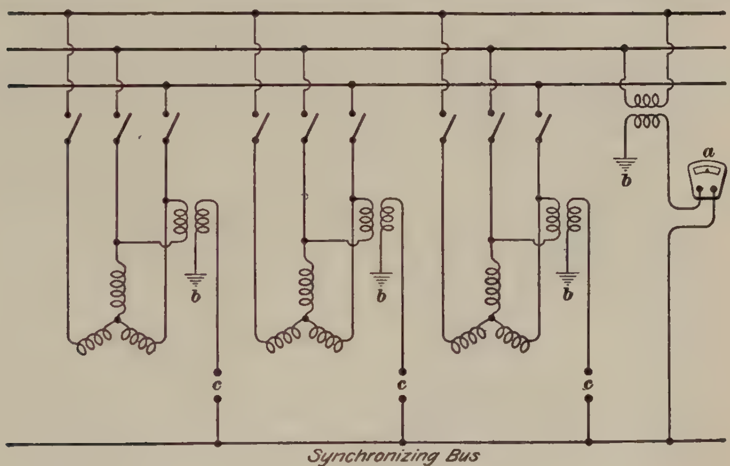


Fig. 22

will be either zero or double the voltage of the potential-transformer secondary pressures, according to the system of connecting the transformers. Another method is to connect the voltmeter in parallel with one of the synchronizing lamps, so that the instrument will show the fall of potential through the lamp.

The voltmeter, when used to show the in-phase relation by its zero indication, is almost as unreliable as an incandescent lamp, because the scale of an alternating-current voltmeter is very fine near the zero point, a considerable change in voltage being required to move the indicating needle a distance that

can be observed. Therefore, the instrument should always be connected for showing the in-phase condition by a reading of double potential.

53. Woodbridge System.—The indication of synchronism by a double-potential reading of a voltmeter, also, is somewhat unreliable; the pressure changes at the times immediately preceding and following the in-phase relation are small in comparison with the changes in phase. To obviate this difficulty, a scheme of connections applicable to three-phase systems has been devised by J. E. Woodbridge. The method is to apply to the voltmeter the resultant of two alternating electromotive forces differing in phase by 60°. By this scheme, the voltmeter is supplied with an electromotive force that has a relatively rapid change at the times immediately preceding and following the in-phase condition. The method is shown in elementary diagram, without the details of instrument switching connections, in Fig. 22, in which *a* is the voltmeter, *b* a ground connection, and *c* a single-pole plug receptacle.

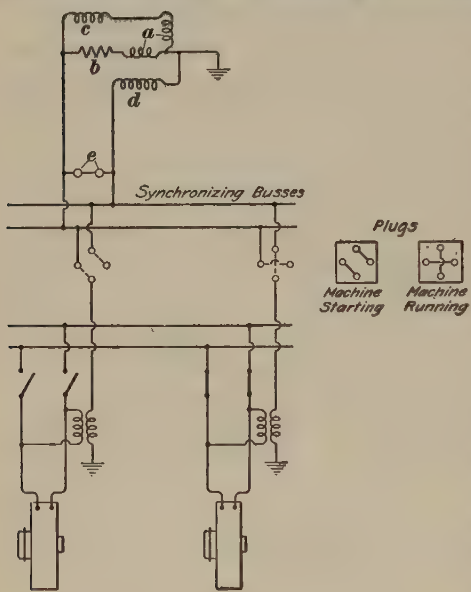


FIG. 23

SYNCHROSCOPE CONNECTIONS

54. Like lamps, a voltmeter cannot indicate the amount of phase difference between two electromotive forces, nor can it indicate which is leading in frequency. For paralleling alternators of comparatively large capacity, synchronism indicating

devices more accurate than voltmeters are considered necessary, and modern stations are therefore equipped with synchroscopes, or synchronism indicators.

A type of synchroscope constructed on the electrodynamometer principle is described in *Alternating-Current Measuring Instruments*. Another instrument, also of the electrodynamometer type, more nearly resembles a synchronous motor

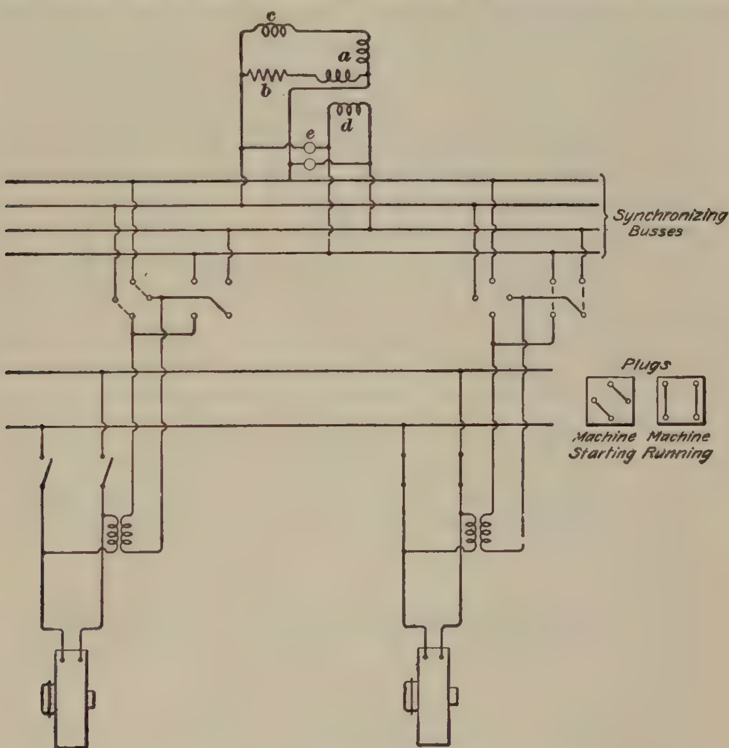


FIG. 24

with field winding excited by alternating current. The armature is of the split-phase type with two coils *a*, Figs. 23 and 24, arranged on a rotatable core at an angle of 90° (mechanically) from each other. The phase splitting is effected by the use of a divided circuit, one branch of which contains a resistance *b* and the other a reactance *c*. The armature windings receive currents

nearly 90 electrical time-degrees out of phase with each other and are supplied by the electromotive force of the starting machine; the field winding *d* is supplied with current by the electromotive force of the running machine. If the frequency of the armature currents is the same as that of the field current, there will be no tendency of the armature to rotate. Any difference in the frequencies, however, causes rotation—one way, if the incoming, or starting, machine is too slow; the other way, if it is too fast. If the two electromotive forces to be synchronized have the same frequency but differ in phase, the pointer of the synchroscope remains in a position indicating the phase difference.

Synchroscope connections with pressure-transformer secondaries grounded are shown in Fig. 23, and Fig. 24 shows connections for transformers not grounded.

With the synchroscope, the necessity of causing the running machine to supply the field of the instrument and causing the incoming machine to supply the armature requires the use of two different plugs, one of which, when connected to the terminals of a receptacle, will cause the field circuit to be excited and the other to make the armature circuit of the instrument alive. Synchronizing lamps *e*, Figs. 23 and 24, are sometimes used in conjunction with a synchroscope. The connections can also be arranged so that the incoming machine is synchronized to the main bus-bars.

SMALL ALTERNATING-CURRENT STATIONS

EXCITER AND ALTERNATOR CONNECTIONS

55. Exciter Generators.—The connections of the apparatus of an alternating-current station are more complex than those of a direct-current plant, for the former must have, in addition to the alternators, one or more exciter sets, the connections of which are almost as complete as those of a direct-current station.

An exciter generator is of small capacity, the amount of energy required for field excitation of an alternator being

generally not more than about 2 per cent. of its own rating. Thus, if a 75-kilowatt alternator were installed, the energy required for its excitation would be not more than $1\frac{1}{2}$ kilowatts; but in practice, such small machines are not used for exciting purposes, and even in a small installation an exciter generator of from 3 to 5 kilowatts capacity is employed.

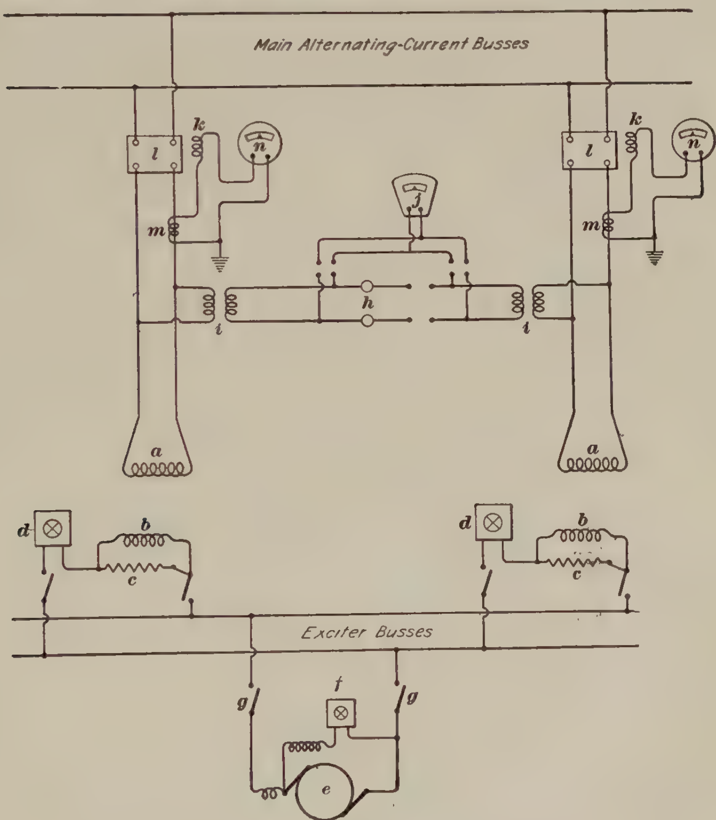


FIG. 25

The exciter generator can be either shunt or compound wound, and there are many installations of each kind in regular operation. The load of the exciter is not changed, except when the station attendant is at hand to regulate its potential. Usually, also, no part of the exciter circuit leaves the station;

therefore, the exciter system is not especially liable to short circuits, which would affect the pressure regulation. There is, then, no very important reason why the exciter generator should be compound wound.

56. Single-Phase Connections.—The alternators of a small station may be single-phase, two-phase, or three-phase. The most modern stations, if supplying any power load, are three-phase, and generally with the armatures star wound in preference to delta wound, as the star winding with the neutral connected is the better for supplying an unbalanced load of single-phase circuits.

There are, however, many single-phase and two-phase installations in service. Fig. 25 shows the principal features of the wiring of a station with two single-phase alternators equipped with simple, hand-operated oil switches with automatic overload release. The alternator armature windings are shown at *a*, the alternator field windings at *b*, the field-discharge resistances at *c*, the alternator field rheostats at *d*, the compound-wound exciter at *e* with its shunt-field rheostat at *f*. The exciter switches *g* are sometimes omitted.

The diagram shows synchronizing lamps *h* connected to the secondaries of ungrounded potential transformers *i* to which the voltmeter *j*, also, is connected through plug switches. In small plants, the use of lamps for synchronizing is common; but the system of wiring shown cannot be taken as standard, because of the diversity of opinion, as to the most suitable form of connection for this work.

The trip coils *k* of the oil switches represented at *l* are energized directly from the current transformers *m* to which the ammeters *n*, also, are connected. This form of connection is in quite general use in small stations; the necessity of relays and of a direct-current operating bus is thereby avoided.

In a one-unit station, the alternator field winding is sometimes connected directly to the exciter terminals, with no exciter switches or alternator field switches in circuit. Also, with a single unit, the synchronizing connections are, of course, omitted.

57. Two-Phase Connections.—The principal features of polyphase alternator connections in small stations are shown in Figs. 26, 27, and 28, each of which is lettered to correspond with Fig. 25.

The wiring diagram of a pair of two-phase generators is shown in Fig. 26. The oil switches have two trip coils, either of which, if energized, can operate the automatic opening devices.

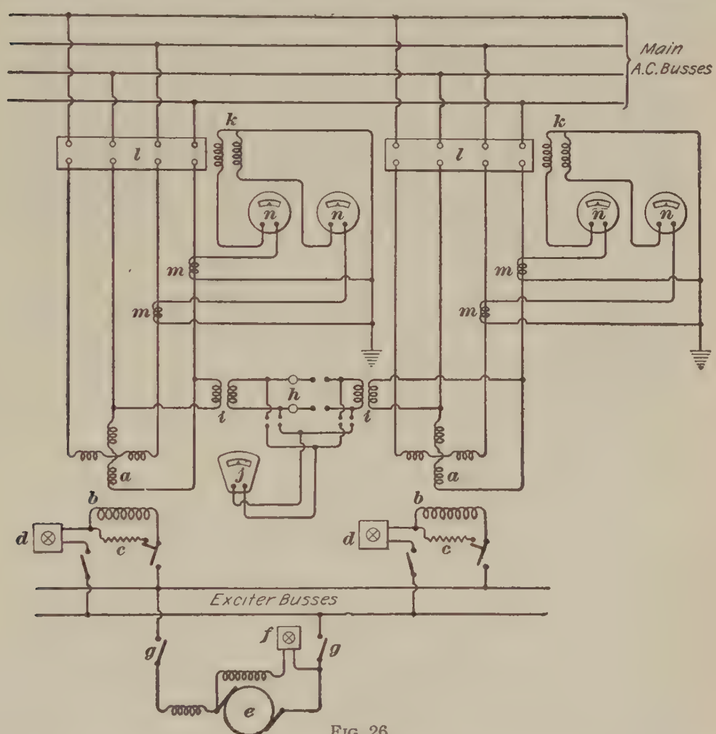


FIG. 26

Each trip coil is in series with a separate current transformer, one on each phase, so that the switch will be automatically opened if an overload occurs on either of the two armature circuits. The current transformers supply the indicating ammeters also, of which there is one for each phase. The voltmeter plug switches on each panel are sometimes arranged so that the voltage of either phase of the machine can be read.

58. Three-Phase Star Connections.—The essentials of the wiring of a pair of Y-wound alternators are shown in Fig. 27. Overload protection is necessary on each phase separately; a trip coil is therefore installed in series with the secondary coil of a current transformer and an ammeter for each phase conductor of the machine leads. The secondaries of the current transformers are usually grounded on one side, and the

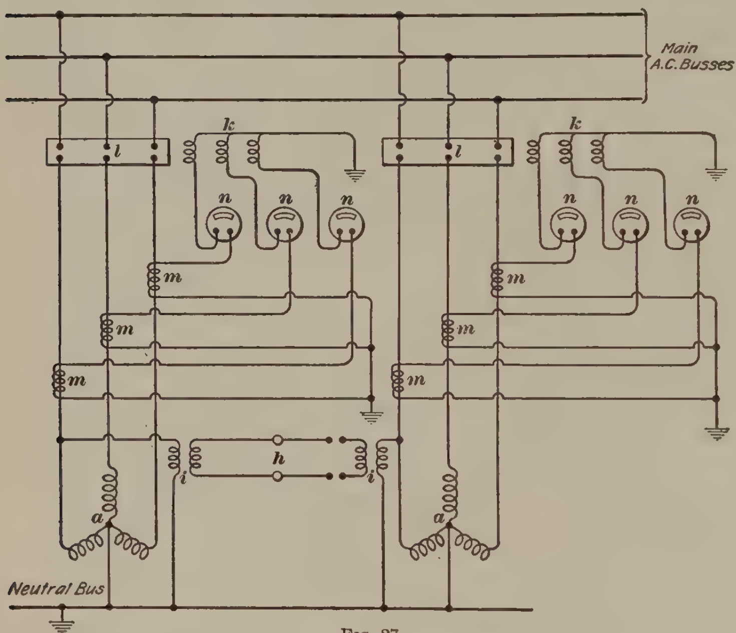


FIG. 27

return side of the trip coils is also grounded, the return circuits being completed through the ground connections.

The most modern practice is to ground the neutrals of Y-wound alternators, in order to limit the potential between any one phase conductor and the ground. One form of ground connection consists of a copper plate, about 3 feet square and $\frac{1}{8}$ inch thick, buried in a thick bed of charcoal deep enough in the ground to be always moist and below the frost line. Such grounds may develop high resistance, owing to the disappearance of moisture from the ground surrounding the plate; a

more efficient ground consists of a number of pipes, each pointed at one end and drilled at a number of places near the point. Each pipe is driven pointed end downwards into the ground to a distance of about 3 feet below the frost line, and is then filled with crushed rock salt and water. The pipes are connected together by a bar or strap of copper and to this bar or strap is joined the neutral connection of the generators. The water and salt are renewed occasionally, and the brine perco-

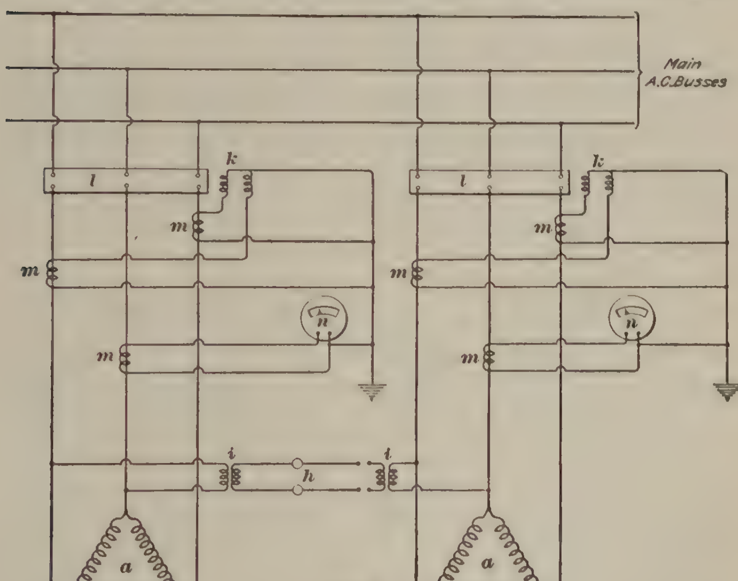


FIG. 28

lates through the holes in the pipes and keeps the ground saturated with a good conducting liquid.

The voltmeter and exciter connections are not shown in Fig. 27. The latter are the same as in Figs. 25 and 26; the former (not shown) are so arranged that the voltage of any phase of any generator can be determined.

59. Three-Phase Delta Connections.—The wiring diagram of two delta-connected, three-phase alternators is shown in Fig. 28. These generators can have no neutral connection to their armatures and are not so well adapted for carrying

unbalanced loads as are the Y-wound machines. When delta-connected generators are used, it is sufficient to use an oil switch with two trip coils and to install current transformers for these trip coils on only two phases of the generators, as shown in the diagram, and this is frequently done. When the load is nearly balanced, current readings on only one phase need be taken, and the ammeter can be connected, either in series with one of the trip coils or in the circuit of a separate current transformer, as shown in the diagram. Sometimes three current transformers and a three-way switch are provided, so that ammeter readings on any phase can be taken from one instrument per generator panel. By providing the panels with suitable plug receptacles, the voltmeter connections (not shown in Fig. 28) can be so arranged that the instrument will indicate the voltage of any phase of any generator in the station. The exciter connections, being the same as in Figs. 25 and 26, are not shown in Fig. 28.

BUSSES, SWITCHES, AND DISTRIBUTING CIRCUITS

60. Busses and Switches.—If the voltage of an alternating-current system is 4,000 or less, the bus-bars are generally installed on the back of the switchboard, and oil switches for generators and feeders are supported on the rear of the panels. The oil switches are manually operated by means of a handle on the front of the switchboard. When the voltage is higher than about 4,000, which is infrequent in small stations, the switches are generally more remotely situated and the mechanical connection is made to the mechanism by longer links, bell-cranks, etc., as described in *Switchgear*. When the voltages are as low as 1,000, or even 2,000, circuits are sometimes equipped with knife-blade switches and fuses. The knife-blade switches have long air breaks and are operated either by a handle on the switch or by a long wooden pole that permits the operator to open the switch with somewhat greater safety. Low-tension stations—that is, those generating from 400 to 750 volts—usually have knife-blade switches and, if automatic protection is desired, air-break circuit-breakers. In such cases, the switchboard bears a considerable resemblance to that of a

low-tension direct-current installation, except for the instruments, which are adapted for alternating-current service.

The distributing circuits in systems of 4,000 volts or less are not always provided with oil switches. In many installations, the automatic protection consists only of high-tension fuses, either of the cartridge type, or of a semi-enclosed form. In order that a circuit may be disconnected for replacing the fuses, knife-blade switches are placed in series with the fuses, preferably on the bus side of the fuse-holder studs.

61. Distributing Circuits.—Distributing circuits from single-phase stations are, of course, all single-phase. From two-phase stations, both single-phase and two-phase circuits supply the distributing systems, single-phase for lighting circuits and two-phase for power service. From the three-phase stations, especially those with Y-wound generators, single-phase circuits supply lighting loads, three-phase three-wire lines are run for power, and four-wire three-phase circuits for combination lighting and power service. On account of the expense of running separate circuits for each kind of service, it is common practice, except in very large systems, to use the combination lighting and power circuits for general distribution and to connect lighting and single-phase power loads between the neutral and each of the different phase conductors, care being taken to balance the connected load properly.

When a grounded neutral system is used, the neutral bus is usually not installed on the switchboard, but at some convenient location in the station, generally near the place where the circuits leave the building.

MEDIUM-SIZE ALTERNATING-CURRENT STATIONS

GENERAL FEATURES

62. Alternating-current stations of medium size, intended for general lighting-and-power service, usually have polyphase generators, the connections of which do not differ essentially from those of the smaller installation. The principal difference between the small and the medium-size station is in the number

and size of the units; the details of connection of such apparatus as synchronizing circuits, protective devices, and distributing circuits; the use of more elaborate equipment, such as circuit-potential and Tirrill regulators; and the more complete use of protective devices.

TIRRILL REGULATOR

63. In order to provide good regulation of the potential at the bus-bars and thus to improve the regulation on the circuits, Tirrill regulators are sometimes installed. It is the usual practice to connect the potential coil of the Tirrill regulator to the secondary of a potential transformer, the primary of which is connected directly to one phase of the leads of the generator to be regulated. If all the generators receive field current from one exciter, the pressure transformer for supplying the Tirrill regulator may be connected to one phase of the bus-bars instead of the generator leads. The direct-current supply for the regulator is generally made selective between exciters by means of a separate switch of small capacity connected to the terminals of each exciter set or, in some instances, is made selective between two exciter busses by similar switches connected to exciter bus-bars.

PROTECTIVE DEVICES AND SYNCHRONIZING CIRCUITS

64. Protection From Overload.—The oil switches in use in the generator leads in stations of medium size where the units are of 200 kilowatts capacity, and upwards, are usually not operated by a trip coil energized directly from the current transformers, but by direct current from operating busses at a potential of about 125 volts. The direct current for actuating the tripping device is sent through the trip coil by a relay that is energized by current from the current transformers in the generator leads. The wiring for these relays and the trip coils of the oil switch is shown in Fig. 29 (*a*), (*b*), (*c*), and (*d*), for single-phase, two-phase, three-phase delta, and three-phase Y systems, respectively. In each diagram, the alternator armature winding is represented at *a*, the oil switch at *b*, a current

transformer at *c*, a relay operating coil at *d*, relay contacts at *e*, the oil switch trip coil at *f*, and the leads to the direct-current operating busses at *g*.

The operating busses are generally supplied from the exciter system, though, in some cases, the supply is from a small storage battery of about 40 amperes capacity installed especially for the purpose. The operating busses connect not only to the

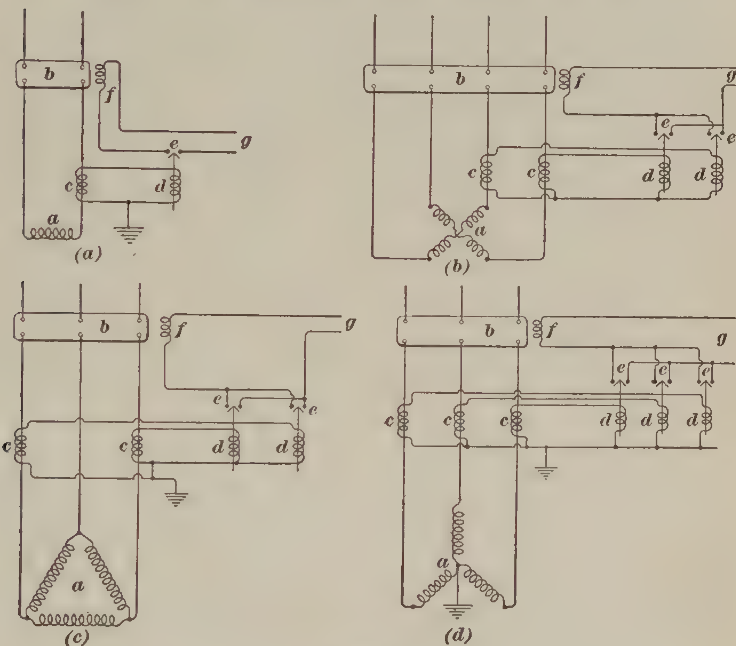


Fig. 29

overload relays, but to all control devices requiring direct current for their operation.

65. Remote-Control Circuit.—In medium-size stations, it is not uncommon to have the entire oil-switch installation subject to remote control, electrically or pneumatically, at the will of the operator. The switchboard then bears, instead of operating handles, only small control switches for energizing the operating coils and for each control switch a pair of signal

lights to indicate whether or not the switch operation has been completed. The wiring diagram of such an oil switch is shown in Fig. 30. When the single-pole, double-throw, control switch *a* is thrown to the upper position, the solenoid of the relay *b* receives current and the relay contacts are thereupon closed, completing the circuit from the direct-current operating busses through the closing solenoid *c* of the oil-switch operating mechanism. The three-way switch *d* is mechanically connected to the oil-switch mechanism, so that closing the oil switch moves the contactor of the three-way switch to the left, thereby closing the operating circuit through the opening coil *e* of the oil switch and through the red signal lamp *f*, the lighting of which indicates that the closing of the oil switch is complete. When the lamp is in series with the opening solenoid, the current in the solenoid is too small to operate the oil switch; when, however, the control switch is thrown to the lower position, the opening coil is connected directly across the operating busses, and the current becomes great enough to operate the switch mechanism and open the main circuit. The opening of the oil switch closes the three-way indicating switch *d* to the right, so that the green signal lamp *g* receives current. The opening coil can also be connected in series with a current transformer to provide for automatic opening of the oil switch, in case of overload. The control switch must be opened, and left open, after the completion of each operation of opening or closing the oil switch.

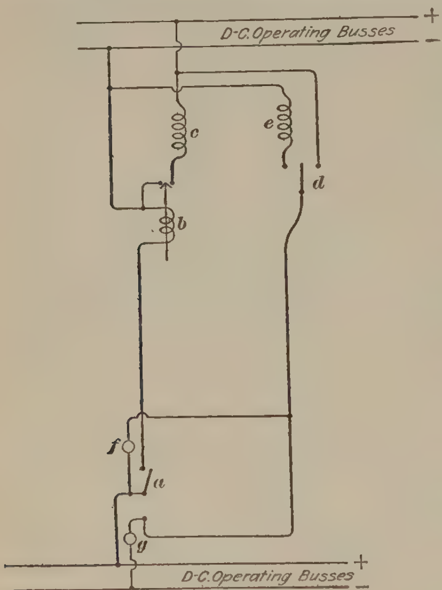


FIG. 30

66. Synchronizing circuits in stations of medium size are generally provided with a synchroscope, on account of the difficulty of performing accurate synchronizing operations by the indications of lamps or voltmeters.

BUSSES AND DISTRIBUTING CIRCUITS

67. Duplicate Bus System.—The service supplied from alternating-current stations of medium size is generally more important than that supplied from the smaller plants. Hence, in order that the interruptions or inconvenience due to construction, repair, or maintenance work on the apparatus may be reduced to a minimum, there are generally at least two sets of bus-bars to which the generator leads and distributing circuits can be connected. The selective switching between different sets of bus-bars can be effected by the use of two separate oil switches, sometimes mechanically or electrically interlocked, or by a set of knife-blade transfer switches so arranged that the switches can be connected to both busses at the same time. Such switches have two blades on a common hinge, but the blades are so arranged that they can swing independently of each other and fit into clips with two receptacles. The switches can thus be *split* between busses and the connection of the machine or circuit transferred from one set of bus-bars to the other without interruption of the supply.

68. Control and Voltage Regulation of Distributing Circuits.—In medium-size alternating-current plants used for general lighting and power, the distributing circuits are usually more completely equipped than in the small plants. The feeders are provided with oil switches having automatic overload release, and in many cases the circuit switches are also electrically remotely controlled at the will of the operator.

On account of the great differences in lengths and loads of feeders, the potential drops therein differ, and it is not possible by regulating the bus voltage to supply uniform pressure over a large area. Long feeders or circuits are sometimes equipped with boosting transformers and the shorter feeders with choking transformers. This method of adjusting the supply of pressure

to the distributing circuits compensates for the different potential drops, due to different lengths of feeders, but not for the change in potential drop, due to change in load. In order to provide for this condition also, potential regulators are used. Potential regulators are capable of being changed at once from boosting to choking transformers, or vice versa, and of raising or reducing the voltage in any desired amount up to the limit of their potential capacity.

Potential regulators are usually installed in one conductor of each single-phase lighting circuit and in each phase conductor of three-phase combination lighting and power circuits. They may be either remotely controlled at the will of the operator, or automatically controlled by means of a contact-making voltmeter. When they are remotely controlled by the operator, a line-drop compensator is generally used to indicate the potential at the distant feeding center.

LARGE ALTERNATING-CURRENT STATIONS

GENERAL FEATURES

69. Alternating-current generating stations for supplying lighting and power for large systems are of two kinds: those distributing energy directly to the feeding centers in the same manner as the medium-size stations and those supplying converting and distributing substations. As the details of the distributing circuits in the first-named type of stations are the same as those in plants of medium size, the following description pertains more particularly to stations supplying converting and distributing substations.

The generators in stations of this class are nearly always three-phase, and usually have armature windings **Y**-connected, with the neutral grounded. Sometimes the ground is made through a cast-iron grid resistance, in order to limit the current in the neutral circuit in the event of a ground on any one phase.

If the generators are not provided with overload protection to open the oil switches in the event of severe overload, such as

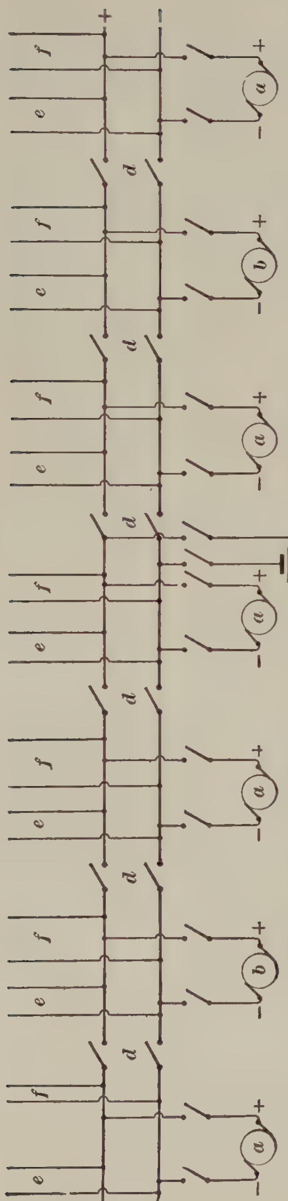


Fig. 31

a short circuit, reactance coils are sometimes connected in the leads between the generators and the bus. These preventive reactances serve to limit the current and thus to prevent damage to the armature windings. Reactances for this purpose are constructed without iron in their cores and are generally self-cooling.

EXCITER SYSTEM

70. In large stations, the exciter system is generally supplied by induction-motor-driven motor generators. The equipment includes, also, steam-engine or steam-turbine-driven exciter generators, which may be used when desired and which must be used to start the system in the event of a total shut down. In addition, some of the large stations are provided with 125-volt storage batteries, which are kept continually floating on the exciter busses. When a storage battery is used, the generators of the exciter sets must be either shunt wound or flat compounded.

Some large stations have a separate exciter and exciter bus for each alternator, the exciters being driven by induction motors supplied with current from the generator leads. With this form of installation, it is necessary to provide *ties* (switches) between adjacent individual exciter busses, so

that any bus can be energized from the others, and the corresponding alternator excited until it is in operation and the individual motor-generator exciter set is started and paralleled to the exciter busses.

In Fig. 31 is shown the arrangement of the exciter system of a large generating station in which a storage battery is floated on the exciter bus-bars; motor-driven exciters are represented at *a*, steam-driven exciters at *b*, the storage battery at *c*, exciter-bus sectionalizing, or tie, switches at *d*, leads to alternator field windings at *e*, and leads to the direct-current operating busses for oil switches at *f*. This station is normally operated with the exciter bus-bars continuous, in order that the storage battery may be effective on all the exciter busses, but is so arranged that the exciter bus-bars can be sectionalized at will. The supply of current for excitation of generators and for the operating bus for all the oil switches pertaining to each unit is taken from the exciter bus-bar section corresponding to that unit.

SWITCHES, BUSSES, AND DISTRIBUTING CIRCUITS

71. Oil Switches.—In large stations, where units are of considerable size (3,000 kilowatts and upwards) and large amounts of energy are handled, oil switches are necessarily remotely controlled, either electrically or pneumatically. Modern installations of large oil switches are practically all provided with electric operating devices, either motors or solenoids. The size and design of the switches are partly dependent on the potential of the circuits in which they are placed, but the barrier type of construction is generally used, in order to prevent an arc in one oil well or compartment from communicating to adjacent phases and starting a serious short circuit, which might do great damage. In addition, there are sometimes used oil switches in which the circuit is not only broken twice in each phase under oil but each break is made in a separate oil well.

72. Bus Construction and Location.—The type of bus construction employed in large alternating-current stations varies according to the voltage of the system, but for voltages

between 5,000 and 30,000, the cellular and barrier form is in general use, in order to confine as much as possible arcs that may occur as the result of a breakdown of insulation. In some of the larger stations, the high-tension bus and switching equipment is placed in a separate portion of the building with fire-walls between the switch room and adjacent parts of the building. The oil switches are usually placed on one floor and the bus construction in a room below, as shown in Fig. 32. The operating mechanism *a* of the oil switch is mounted on the top of the oil-switch compartment *b*. In addition to the oil switch, a knife-blade disconnecting switch *c* is provided.

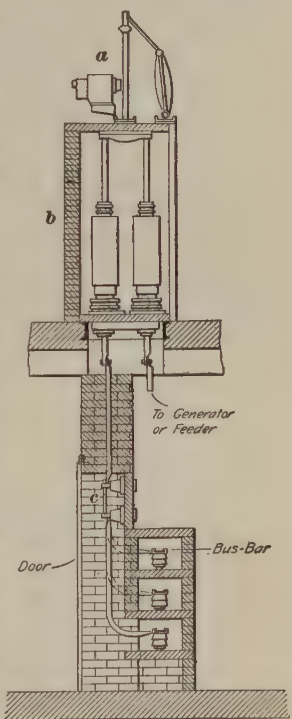


FIG. 32

73. Bus Systems.—The systems of arrangement of busses in alternating-current stations of large size are almost as numerous as the stations, but they may be roughly divided into five general classes: one-bus system, single sectionalized bus system, ring-bus system, duplicate bus system, and duplicate sectionalized bus system.

In the **one-bus system,** all generators and feeders connect to one set of bus-bars, which are continuous from one end of the switchboard or bus compartment to the other. Such a system is not adapted to flexibility of operation, and in order to avoid this disadvantage, the bus is sometimes divided into a number of sections, one for each generator, forming the **single sectionalized system** shown diagrammatically in Fig. 33, in which *a* indicates a generator and *b*, a generator oil switch. The bus-bars can be made continuous, when desired, by means of bus-tie oil switches *c*.

With the arrangement of Fig. 33, any section can be taken out of service for repairs or construction work; but if the section taken out is not at one end of the bus system, the sections on each side of the idle one are isolated from one another. To avoid such a condition, the **ring system** shown in Fig. 34 is employed.

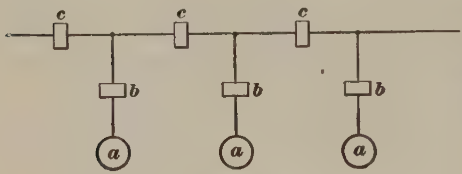


FIG. 33

The ring system permits any bus-section to be taken out of service, but, like the single sectional system, it requires that the generator connected to that section be taken out of service, also. This difficulty is obviated by the **duplicate sectionalized bus system,** Fig. 35, which consists of duplicate sets *a* and *b* of bus-bars, to either of which any generator *c* can be connected by selective switching provided by oil switches *d* and *e*. The use of a reactance in the generator leads is indicated at *f*. If

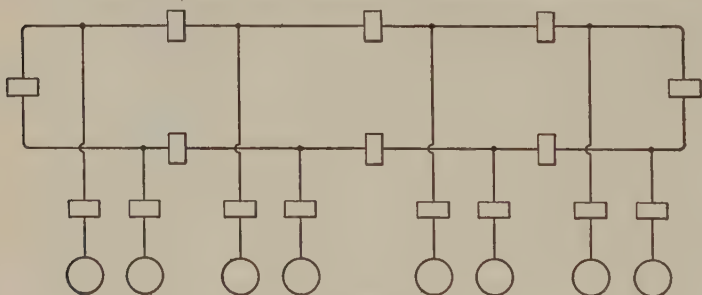


FIG. 34

the distributing circuits, also, are made selective between the two sets of bus-bars, a high degree of flexibility of operation is secured.

74. Distributing-Circuit Connections.—Distributing circuits are connected to the bus-bars through oil switches, and if duplicate busses are provided, can be made selective in switching by installing two oil switches. The use of a single

oil switch and a set of transfer knife-blade switches, as described in connection with medium-size aternating-current stations is not frequently resorted to in large stations, where the circuits carry large amounts of energy, especially if the voltage is high. The most modern method of connecting distributing lines and circuits is the **group system,** by which a small group of circuits, usually four or five, are connected through oil switches *g* to a common *group bus h*, Fig. 35, which has two switches *i* and *j*, each of which connects to a separate set of distributing bus-bars, thus making the group selective in switching between the two busses.

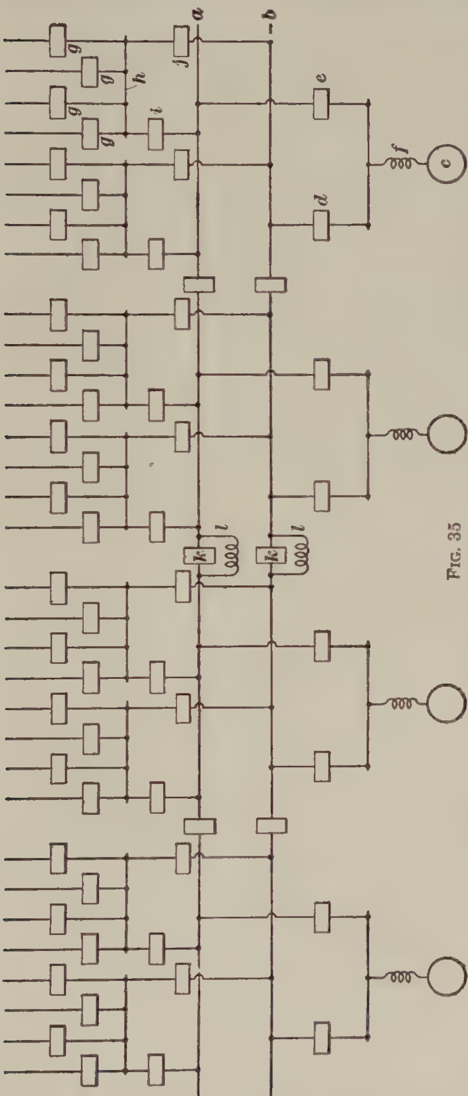


FIG. 35

75. Sectional Operation.—Some large alternating-current stations are operated sectionally—that is, with their bus-bar system separated in two or more main divisions—on account of the danger of connecting together large amounts of generating capacity, which, in

the event of a short circuit on the bus-bars, might cause enormous damage, not only to the bus construction but to the switches and generators. The sectionalized operation is effected by opening a bus-bar tie-switch k, Fig. 35, between two divisions of the distributing busses, leaving connected to each division an amount of generating capacity, which is considered safe. As the most favorable operating condition exists when all the generating units are in parallel, sectionalized operation may effect economy unfavorably; and, in order to permit parallel operation of sections, but, at the same time, to limit the current into one section from adjacent sections, a preventive reactance l is sometimes installed in each phase conductor between the sections at the point where the bus-bar tie-switch is open. The reactances permit ordinary amounts of energy to pass between the sections, thus affording all the advantages of parallel operation; but they choke back any large amounts of energy and thereby serve to limit the extent of the damage in case of a short-circuit.

ELECTRIC SUBSTATIONS

Serial 1647 Edition 1

INTRODUCTION

PURPOSE OF SUBSTATIONS

1. Electric energy in large quantities can be produced more economically in one or two large generating stations containing large units than in several stations having smaller units and, possibly, having less complete facilities for handling coal or for obtaining condensing water.

While economy in generation makes large stations desirable, the highest economy of distribution requires the shortest possible length of distributing circuit; a condition which, if fulfilled, would necessitate a large number of distributing centers scattered throughout the load territory. Even in places where the load density is great, it is not always desirable to build a generating station, as facilities for obtaining coal, removing ashes, and providing condensing water may be so poor as to make the cost of operation too great, or the cost of land may be so high that the interest on the investment in real estate would make the station unprofitable.

Electric substations offer a solution of the problem just presented. They do not require as much space as generating stations, and, when necessary, can be installed in basements or other places where generating plants would be uneconomical or impossible. There is also less difference in operating economy between large and small substations than between large and small generating stations. These conditions permit the use

of a larger number of distributing centers than would be possible with generating plants only, and the distributing circuits are thus shortened.

In hydroelectric developments, the generating station is necessarily located near the water supply, which may be situated in a place remote from the market for the electric energy. Substations are then necessary to a complete system of distribution, because the receiving apparatus cannot use the energy in the high-pressure form that is required for long-distance transmission.

2. In the accomplishment of its purpose a substation may perform one or more of the following duties: The transformation of alternating current at one voltage into alternating current at another voltage; the conversion of alternating current into direct current; the change of one alternating current into another of different frequency.

3. Direct-Current Substations.—For variable-speed power service, direct-current motors are usually selected. Direct current is therefore usually demanded in the congested business districts of large cities, in large industrial plants, and in certain classes of electric-railway service. In such cases, if the general distribution is by alternating current, direct-current substations equipped with synchronous converters, or motor-generators, are necessary.

4. Frequency-Changer Substations.—Large alternating-current generators operate most satisfactorily at low frequency. Also, electrical energy can be transmitted most economically in the form of low-frequency current, because the reactive voltage drop in a conductor is directly proportional to the frequency. Most long-distance transmission of electricity is therefore accomplished at a frequency of 25 cycles. However, some consuming devices, such as certain types of electric lamps, demand for proper operation a frequency as high as 60. Frequency-changer substations are installed to convert the low-frequency alternating-current energy carried by transmission lines into higher-frequency alternating-current energy for

distribution among consuming apparatus. Conversely, frequency-changer substations can be employed to convert 60-cycle energy generated mainly for general lighting and power service into 25-cycle energy for alternating-current railway service.

5. Transformer Substations.—Transformer substations are used to change the high-tension alternating-current energy of long-distance transmission lines into lower-tension energy for local distribution among general lighting and power consumers. They are also employed on alternating-current railways to convert the high-tension energy from the generating station into energy at a tension low enough for the alternating-current railway motors.

SIMILARITY BETWEEN SUBSTATIONS AND GENERATING STATIONS

6. A substation, being a distributing center, has, in general, the same kind of distributing apparatus as a generating station of the same capacity distributing the same service. It is not uncommon to install substation apparatus in old steam plants and to connect the substation machinery to the generating plant distributing busses. In general, the same distributing busses, feeders, circuits, and switches that are suitable for a generating plant are suitable for a substation supplying the same amount and kind of load.

Motor-generator substations supplying either direct or alternating current have electric connections of their generators, switches, and busses very similar to those of generators driven by prime movers such as steam engines or water turbines.

High-tension bus and oil-switch construction in a substation is usually similar to that used in an alternating-current generating station of equal capacity and voltage, with the exception that it is common practice to provide automatic overload protection for substation apparatus and somewhat less common to do so for the generators in a generating plant. In addition, overload relays are commonly used in connection with the oil switches on outgoing lines from generating stations, whereas

similar protection for the substation ends of the lines is generally not provided.

The substation differs from the generating station in the type of apparatus used and in the much larger kilowatt capacity that can be installed per unit of floor space or per unit of cubic contents.

DIRECT-CURRENT SUBSTATIONS

PRELIMINARY REMARKS

CLASSIFICATION

7. The machinery employed in direct-current substations for converting alternating current into direct current is of three kinds; motor-generator sets with induction motors, motor-generator sets with synchronous motors, and synchronous converters, frequently called rotary converters. Direct-current substations can therefore be classified, in general, as *motor-generator substations* and *synchronous-converter substations*. They can be classified also as *light-and-power substations* and *railway substations*, according to the kind of service in which they are employed.

GENERAL ARRANGEMENT

8. In Fig. 1 is shown, roughly, the arrangement of some of the equipment of a direct-current railway substation. The high-tension transmission line wires enter the building through a protected opening in the rear wall. Connection to the high-tension bus-bars *c* is made through disconnecting switches *a* and choke coils *b*. From the bus-bars, wires lead to disconnecting switches *d*, remotely controlled oil switches *e*, current transformers *f*, and main transformers *g*. The synchronous converter *i* is connected to the secondaries of the transformers through reactance coils *h*, which aid in the regulation of the

direct-current voltage of the converter. The direct-current equipment, such as switchgear, not shown, is practically the same as a direct-current railway generating station of equal capacity.

NUMBER AND CAPACITY OF UNITS

9. The selection of substation units as to size and number should be made only after the actual load is known and the prospective load is estimated. Though most substation

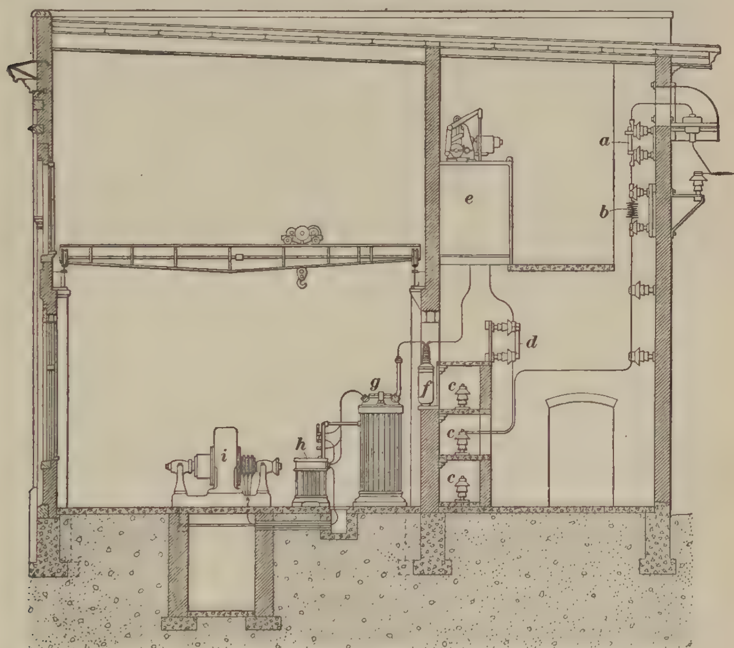


FIG. 1

machinery is fairly reliable, any electric apparatus is subject to various forms of trouble that may temporarily put it out of service, and the best practice is, therefore, to install more than one unit in each substation. Better economy is obtained from the larger units, but when such a machine is disabled a large percentage of the substation equipment is shut down, and for

this reason also it is usually considered good practice to divide the substation capacity among two or more machines.

It is not, however, good practice to install too large a number of machine units. If the conditions permit the use of fairly large units, not more than four to six machines should be installed. These will usually provide all the flexibility of operation needed and they will require less attention, care, and expense for maintenance than will a greater number of machines of the same combined capacity. Furthermore, the smaller number of machines will require a smaller initial investment of capital.

However, in some special locations, as in basements, insufficient headroom limits the size of machinery, and the installation of a considerable number of small units becomes necessary.

Similarity of units as to size and design is desirable, as it reduces the number of emergency repair parts to be kept on hand, and, in some cases, reduces the size of the stock of operating supplies, such as brushes.

MISCELLANEOUS EQUIPMENT

10. High-Tension Bus System.—If the voltage of the high-tension transmission system exceeds about 5,000, the high-voltage conductors of the substation should be kept suitably isolated from one another by fireproof barrier construction. If the line pressure is as high as about 30,000 volts, the barrier or cellular construction is unnecessary, as the violence and destructive effects of an arc between phase conductors is dependent on the current available, and the current is more limited in systems of such high-potential.

The form of arrangement of the high-tension busses depends somewhat on the number of transmission lines and the number of substation machines. If there is more than one transmission line, and more than one unit, flexibility of operation is increased by dividing the high-tension busses into two sections, with a bus tie-switch between them, and connecting one

line and one or more machines to each section. This arrangement permits one part of the substation to be shut down independently of the other if any repairs are to be made.

In general, the alternating-current bus construction in a substation can be less elaborately arranged than that in a main generating station, but it must be at least as good and as safe as would be required in an alternating-current generating plant equal in capacity and voltage to the substation.

11. Oil Switches.—In the selection of oil switches, the same rule as to quality and safety applies; but it may be necessary to choose a type of switch that is adapted to the special conditions at hand. For example, the amount of floor space available may be limited so that a very compact switch may be much better than one occupying more room.

In substations of small or moderate size, transmission line switches for use on systems of 15,000 volts or lower may be hand-operated, remotely controlled. Bus tie-switches for connecting the different sections of the high-tension busses, if not required to carry more than about 800 amperes, may also be hand-operated, remotely controlled.

12. Direct-Current Switchgear.—A direct-current substation should have a direct-current switchboard and switchgear similar to that installed in a generating plant of the same capacity and for the same kind of service. The connections of armature leads, armature switches, rheostats, busses, instruments, and feeders will be the same as would be required for steam-driven units of the same capacity.

13. Motor-Driven Generators.—The generators of motor-generator units differ in no important respects from those used in steam-driven sets of the same capacity and speed. If the generator is directly connected to the motor, both motor and generator will have the same speed; and it is, of course, necessary that the generator be one adapted for operation at the speed at which the motor runs. If the generator is belted to the motor, the proper speed relations are secured by selecting pulleys of proper sizes. If belted units are used, the best

arrangement is one that gives a sufficient distance between the pulleys to permit the use of a slack belt.

14. Grounding Belt-Driven Machines.—Belts running at high speeds sometimes cause static electricity to be generated, and if the motor or generator is insulated from the ground there is danger of the static charge puncturing the insulation of the machine; the frames of belted machines therefore should be grounded. If it is objectionable to have them grounded through conductors having any considerable carrying capacity, the ground connection can be of high resistance, such as a lightning-arrester carbon, or the filament of an incandescent lamp connected between the machine frame and ground.

If some local condition makes a complete metallic ground connection undesirable, the intensity of the static discharge can be greatly reduced by connecting to the frame of the machine a metallic conductor with a number of sharp points and placing near the ends of the points, about $\frac{1}{8}$ or $\frac{1}{4}$ inch distant, a metallic conductor that is connected to ground. The size of this ground connection is not important except as its mechanical strength may be affected, and it should be installed in such a position that it will not be liable to be broken. It is, in effect, a lightning arrester in continuous discharge during the operation of the machine. In some cases, relief from static stress is afforded by arranging a grounded conductor with a number of points projecting near the moving belt.

15. Shunt-Field Connections.—In general, it is good practice to install direct-current generators without switches in their field circuits, the shunt-field terminals being connected directly to the armature leads. However, it is sometimes desirable, as a result of some special condition or requirement, to have facilities for readily opening the shunt-field circuit. These special conditions are more common to motor-generator substations than to main generating stations. Whenever such conditions exist, a quick-break field switch and a field-discharge resistance are used.

TRANSFORMERS

NUMBER, CONNECTIONS, AND CAPACITY

16. Number.—In the selection of step-down transformers for supplying rotary converters or motors of motor-generator sets, there is considerable latitude. If the transmission is two-phase, two single-phase transformers are generally installed, because if one is disabled it may be conveniently replaced by another. If a three-phase transmission system is used, three single-phase transformers or one three-phase transformer can be used, depending on the conditions. Three single-phase transformers are more expensive and occupy more floor space than one three-phase transformer of equivalent capacity. If one of an installation of three single-phase transformers is disabled, the injured one can usually be disconnected and replaced more quickly, and repaired at less expense, than can one three-phase transformer; if they are delta connected, the injured transformer can be disconnected in a few minutes and a part of the load can be carried on the other two, operating on an open delta, or **V**, connection. However, modern transformers are so well built and so well protected by lightning arresters, choke coils, automatic overload oil switches, and other devices that the most common practice now is to use one three-phase transformer rather than three single-phase transformers.

17. Connections.—In the use of either of the two forms of three-phase transformers, the windings may be connected either star or delta. Star-connected primaries are generally used for potentials higher than about 10,000 or 15,000 volts. When transformers are purchased, the specifications are usually prepared with particular reference to the form of connection to be used; but, in many cases, transformers already on hand, sometimes those used in connection with some other installation, must be adapted for use. In such a case, the choice as to form of connection is generally limited.

18. Capacity.—Step-down transformers for use with induction motors must be of sufficient size to carry the load at

the power factor that the motor will have when fully loaded. The manufacturer is generally able to state with a reasonable degree of exactness what the power factor of a motor will be at various loads. If, then, the output in kilowatts is divided by the product of the motor efficiency and the power factor, the result will be the input in kilovolt-amperes, and the transformer should be rated for at least as much as this.

COOLING METHODS

19. Oil-Cooled Transformers.—Transformers can be selected from three general types; oil-cooled, air-blast cooled, and oil-and-water cooled. Oil-cooled transformers are quite satisfactory in capacities as great as about 1,500 kilowatts, and air-blast transformers of 4,500 kilowatts capacity are successful; in larger capacities oil-and-water cooling is more general.

Oil-cooled transformers require the installation of no auxiliary apparatus for cooling. They should be so situated that the circulation of air around them will be good, and care should be taken, as far as possible, that the air is not first heated by the substation machines. Only about 12 per cent. of the total heat liberated from apparatus in the substation comes from the transformers, and a considerable amount of heat is thrown off from the converting machines themselves. For this reason, it is desirable that the locations of windows, transformers, and machines be such as to provide a good circulation without sending heated air around the transformer cases.

20. Blower System.—Air-blast-cooled transformers are comparatively inexpensive to purchase, but require the installation and operation of a blower fan for supplying the cooling air. The fans used are generally of the blower type, that is, fans capable of delivering a moderate amount of air at comparatively low pressure, such as $\frac{1}{2}$ to 1 ounce per square inch.

If there are a number of substation units, one blower set may supply air for the transformers of all of them; but duplicate sets are generally installed, so that the breakdown of one will not affect the entire plant. The unit system goes to the other

extreme of providing a separate blower fan and air chamber for the transformers of each unit. When this is done the blower motor is usually left switched permanently to the leads of the converting unit and it starts and stops with the main machine.

21. Blower Drive.—The fans for air-blast cooling of substation transformers may be, and are in some cases, driven by induction motors supplied with current directly from the line; but motors of such small capacity are generally made for low voltage, and therefore it is better and more usual practice to install step-down transformers for supplying all of the substation auxiliaries and to use 220- or 230-volt motors.

The size of the motor used for driving the fans is such that it will operate at almost full-rated load when the fan is furnishing air for all of the transformers it will ever have to supply. In practice, it is found that a 5-horsepower or 7½-horsepower motor is large enough to drive fans for supplying the transformer equipment for two 500-kilowatt units, and a 20-horsepower motor is sufficient for use in connection with four 1,000-kilowatt units.

In some small installations, especially where there is but one unit, it may be possible to omit the special blower motor altogether and to drive the air-blast fan belted from a pulley on an extension of the shaft of the motor-generator or rotary converter. This arrangement has the advantage of always operating when the unit is in operation, reducing expense, and leaving out one piece of apparatus, the disability of which might affect the safe operation of the entire unit.

22. Air Supply.—The air for cooling substation transformers is preferably taken from outdoors through an opening remote from the place where the heated air is discharged from the operating room.

Air taken from a point near the ground may carry considerable dust, which may partially choke the air passages in the transformers and thus produce a condition that causes overheating. Various methods are used to separate the dust from the air, but in any given case only a limited number of these can be applied.

Air taken from a stack reaching above the roof of the building will probably be fairly free from dust. If a stack cannot be used, a large chamber, or passage, between the fan discharge and the transformers is very valuable. A large passage causes a great reduction in the velocity of the air, so that much of the dust, at least the heaviest part, settles to the floor, from which it can be removed readily.

When neither of these methods is available, some form of air-cleaning device is sometimes used. In Fig. 2 is shown an arrangement that offers a large amount of screening surface for a given cross-section of air passage. The screens *a*, of copper or bronze wire, are placed diagonally between horizontal sheet-iron plates *b*. The screens, though effective in removing the large dust particles, admit the very fine dust, which is really the most objectionable in a transformer. A more effective screen is one made of cloth, either cotton or woolen, but preferably of woolen. A cloth screen can be made as thick as desired, and any required amount of screening action secured. Air-blast equipment used in connection with screens must be relatively large in capacity to compensate for the reduction in air pressure caused by the screens.

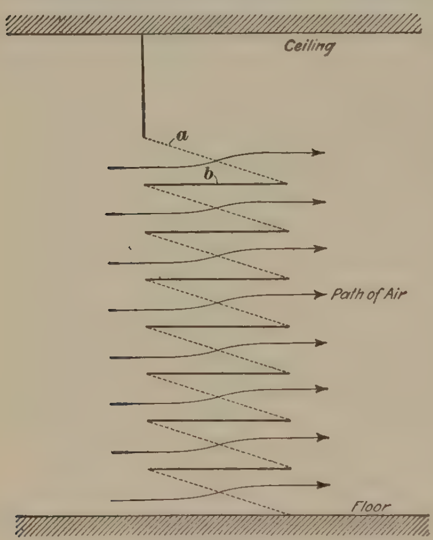


FIG. 2

23. Oil-and-Water-Cooled Transformers.—Transformers that are oil-and-water cooled require a continuous supply of cold water during operation. If there is available a supply from a system of waterworks having a head at least slightly higher than the tops of the transformers, the cooling

coils can be connected thereto, and no further auxiliary equipment will be needed. If no such water supply is available or convenient, it may be necessary to take water from a well, river, or lake and to circulate it through the cooling coils by means of a small pump. One pump, supplied with power either from a separate motor or from an extension of the shaft of a converting unit, can be used for several banks of transformers. The required capacity of the pump will depend on the amount of water to be circulated and also on the distance through which the water must be lifted. Unless the lift is considerable, the pump can be quite small, even for a large installation of transformers, because a small amount of water, with its high specific heat, will cool a comparatively large amount of oil.

Water containing a great deal of scale-forming, or pipe-clogging, deposit will soon form a thick coating inside the cooling coils, not only limiting the flow of water but reducing the rate of flow of heat from the oil to the water. For this reason, the character of the water supply is very important when water-cooled transformers are to be used.

CHOICE BETWEEN SYNCHRONOUS CONVERTERS AND MOTOR-GENERATORS

24. The choice between synchronous converters and motor-generators for a direct-current substation is dependent on cost, economy, grade of service required, and the kind of alternating-current supply available.

For several years after synchronous converters came into general use, 60-cycle converters were considered undesirable because of high commutator speeds and the liability to flash over between adjacent brush-holders. Improvements in both electrical and mechanical design have practically removed these objections, and converters operating on the higher frequency are successful even under the difficult conditions met with in direct-current railway work at high voltage.

Any variation in the alternating-current voltage supplied to a synchronous converter at once produces a variation in the

direct-current voltage; but as long as the voltage of the supply is maintained the machine is not affected by moderate changes in frequency. Therefore, if the alternating-current supply has a constant frequency but a fluctuating voltage, motor-generators give better service than synchronous converters when close pressure regulation of the direct-current output is required. If the voltage is well maintained and the frequency is variable, the synchronous converter is better. In railway service, and in most factories, very close pressure regulation is not required and synchronous converters are usually employed. Synchronous converters, including the necessary transformers, are generally less expensive in first cost and more economical in operation than motor-generators. Such converters are, therefore, in quite general use, even in places where motor-generators would give better pressure regulation.

25. A synchronous converter that normally transforms alternating current into direct is said to be *inverted* when it receives energy from the direct-current bus-bars and tends to supply alternating-current energy to the line. An objection to the use of synchronous converters is their tendency to speed up dangerously when inverting into inductive loads at time of interruption to the supply from the alternator. Such machines are therefore equipped with over-speed limit devices. The tendency to high speed occurs on failure of alternating-current supply when the converter is feeding a direct-current system having other sources of supply. The converter then becomes inverted and will speed up if the field is weak or is demagnetized by lagging alternating current.

Induction-motor-driven generators are the simplest to install and the simplest to operate, but are somewhat objectionable on account of their effect on the power factor.

Synchronous-motor-driven generators are the most expensive of the three classes of apparatus considered, and their operation is a little more complicated than that of induction-motor-driven sets. Synchronous motor-generators can be operated with a good power factor and are useful for neutralizing the lagging power factor produced by induction motors.

MOTOR-GENERATOR SUBSTATIONS WITH INDUCTION MOTORS

GENERAL REMARKS

26. As the induction-motor installation is practically the same for all the different classes of substations using induction-motor-driven generators, the induction-motor end of the substation will be treated here without special reference to the generator end.

27. The capacity of the motor selected for driving a generator must be such that it will not be overloaded when the generator is supplying its full-rated load. The capacity of the motor must, therefore, be greater than that of the generator by an amount equal to the losses of the generator. Most manufacturers in designing motor-generators generally use a motor that slightly exceeds this requirement.

28. Induction motors are designed for use on circuits of voltages as high as 6,600. Therefore, if the transmission voltage is not higher than 6,600, general practice is to provide induction motors that will operate on full line pressure. If the line pressure is higher, step-down transformers are almost always used.

STARTING METHODS

29. Starting From Transformers.—For starting induction motors of a size suitable for the driving machine of a motor-generator, two means are available. When step-down transformers are used, the least expensive form of starting equipment is made by connecting double-throw switches to low-voltage taps taken from the secondary windings of the transformers. Ordinarily, an induction motor starts very well when supplied with half its normal running voltage, and one double-throw switch connecting the motor primary first to a half-voltage tap and then to the full secondary pressure terminal is all that is required. Such a connection is shown in Fig. 3,

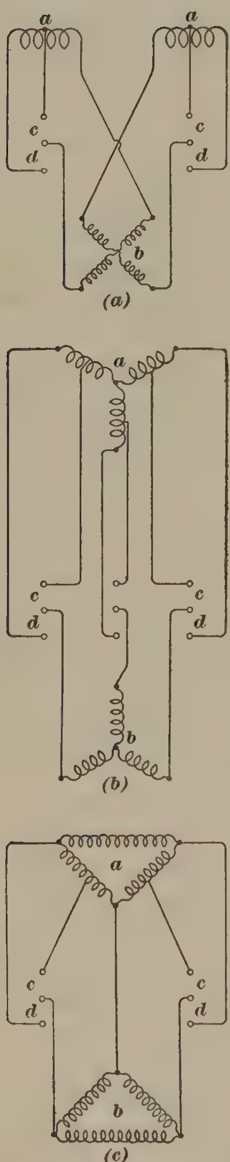


FIG. 3

in which the arrangement for a four-wire two-phase system is shown in (*a*), for a three-wire, star-connected, three-phase system in (*b*), and for a three-phase delta connection in (*c*). In each diagram the secondaries of the step-down transformers are represented at *a*; the stator, or primary, windings of the induction motor at *b*; the starting position of the motor switch at *c*; and the running position at *d*.

30. Other Starting Devices.—If an induction motor is to operate on full line pressure without transformers in circuit, a starting device must be provided. This device usually consists of an oil-switch or a circuit-breaker and two or more autotransformers. The switching device must have the requisite number of contact positions and it may be mounted with or separate from the autotransformers. Separate mounting is the practice with large starters. When the parts are assembled as one unit it is variously called an autostarter or a starting compensator, according to its maker. The switch serves to change connections so as to obtain reduced voltage for starting and full voltage for running. Automatic protective devices are usually provided for overloads and very often for both overloads and low voltage. In some cases the switches are simply oil circuit-breakers so interlocked that they can be closed only in the right order.

One starting device can be so connected as to be used for starting any one of a considerable number of motors. The

autotransformer *a*, Fig. 4, is connected through an oil switch *b* to the running busses, which are supplied with full line pressure, and the low-voltage terminals are connected to special starting busses to which any of the motors can be connected through their individual starting switches. The two single-throw switches *c* connected to the motor leads can be replaced by one double-throw switch *d*, in order to save expense; but

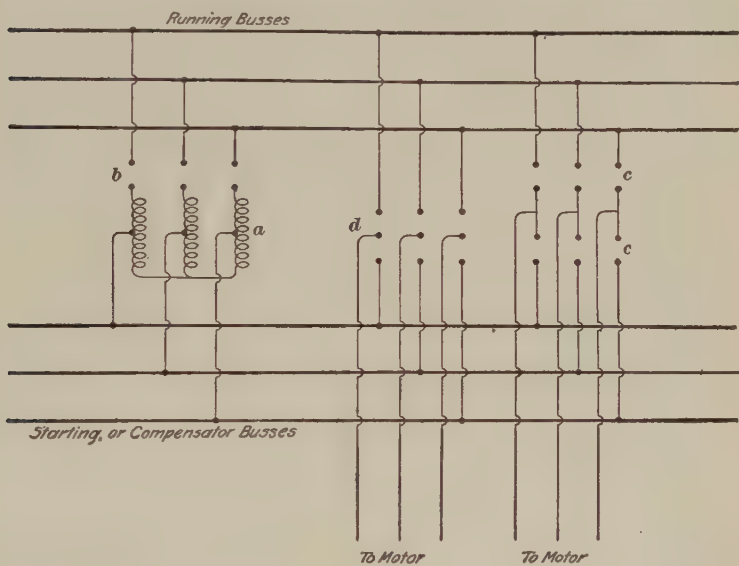


FIG. 4

two single-throw switches made interlocking, either mechanically or electrically, are safer, especially in connection with voltages greater than about 2,200.

INSTRUMENT EQUIPMENT

31. Potential Transformers.—For supplying pressure to alternating-current voltmeters, wattmeters, and watt-hour meters in substations, potential transformers are generally used. One pressure transformer, if of sufficient capacity, can be used for supplying instruments for several machines operated

from the same alternating-current busses. When this is done, it is common practice to run a small pressure-wire bus, of about No. 12 or No. 14 B. & S. gauge wire, along the rear of the switchboard panels of these machines. The pressure bus is supplied from the transformer and taps for the instruments are taken off wherever required.

Pressures for wattmeters must not be taken from potential transformers connected to a high-tension bus other than that which supplies current for the current coils of the wattmeter if there is any possibility of the potentials on the two busses being out of phase with each other, as the wattmeter indications will then be unreliable.

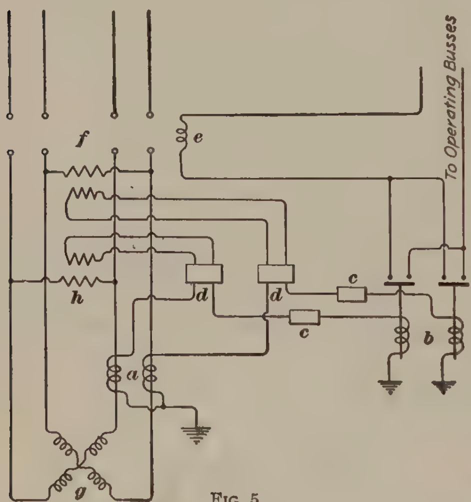


FIG. 5

32. Current Transformers. For the operation of ammeters, wattmeters, and overload relays, current transformers are used in the leads from the busses to the induction motors of substation motor-generator sets. In order that they may protect as much as possible of the apparatus, current transformers should be in the circuit as near as possible to the machine oil switch and on the machine side of it.

The current transformers should be so chosen that they will not be overloaded when the motor-generator is overloaded by 50 per cent. of its normal rating. Modern instruments and relays are usually made with 5-ampere windings, and the current transformer ratio should be such as to give the proper secondary current values for these devices. Thus, if the normal rating of the motor is 60 amperes, the primary of the current transformer should have a capacity of 90 amperes. Its ratio

of transformation, to give a 5-ampere secondary current, would be 90:5, or 18:1.

33. Ammeter, Wattmeter, and Overload-Relay Connections.—The use of an ammeter in the motor circuit of a motor-generator is, of course, an item of some expense, but, though the approximate current input can be figured from the output, the calculation is so long that it is generally not done, and the machine may become overloaded in current before the operator becomes aware of it, especially if there is a reduction of line voltage. For this reason, an alternating-current ammeter should always be installed in each motor circuit, although, in practice, they are generally omitted from the motor leads of small units and are only occasionally installed in connection with large units.

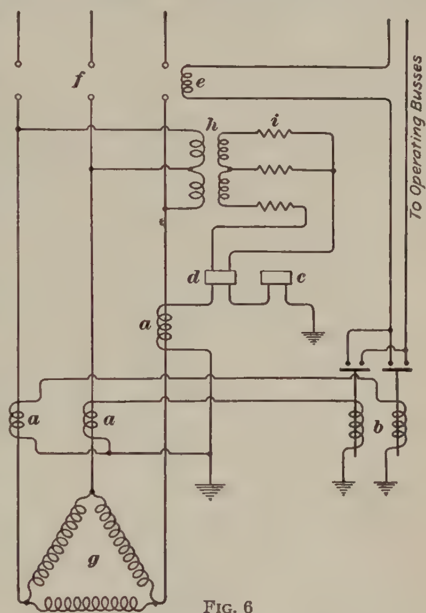


FIG. 6

In Figs. 5 and 6 are shown the connections of current transformers *a*, overload relays *b*, ammeters *c*, and wattmeters *d* on two-phase four-wire and three-phase three-wire installations, respectively. In case of overload, the relays complete the circuit from the operating bus through the trip coil *e* of the oil switch *f*, which is thereupon opened, protecting the motor windings *g*. The potential circuits of the wattmeters are connected to the secondaries of potential transformers *h*. An artificial neutral is secured on the three-phase system, Fig. 6, by means of a **Y** box *i*, in order that the wattmeter may receive the star pressure of the system. The current connections are made through the ground, as indicated.

When a three-phase transmission system is supplied by delta-connected generators or transformers, the use of only two current transformers and two relays is sometimes permissible, but one current transformer and one relay on each phase is better. When a three-phase transmission system is supplied from star-connected apparatus with a grounded neutral, each phase should be equipped with a current transformer and a relay.

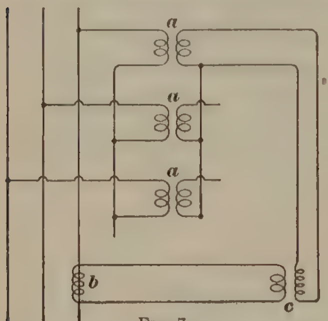


FIG. 7

34. Watt-Hour Meter Connections.—The kilowatt-hour input to the motor generators of substations can be satisfactorily measured by a single-phase integrating wattmeter, or watt-hour meter.

If the transmission is two-phase, a watt-hour meter installed in one phase is sufficient. The instrument will record only one-half the energy input, but the totals can always be correctly determined by multiplying the instrument readings by two.

If the transmission is three-phase, current connections from one phase and star pressure connections from the same phase supply the single-phase instrument. If three potential transformers are used for supplying pressure for the meter, they should be connected **Y**, as shown in Fig. 7, in which *a* is a potential transformer, *b* a current transformer, and *c* the windings of the watt-hour meter. In this case the actual energy input will be three times that shown by the watt-hour meter.

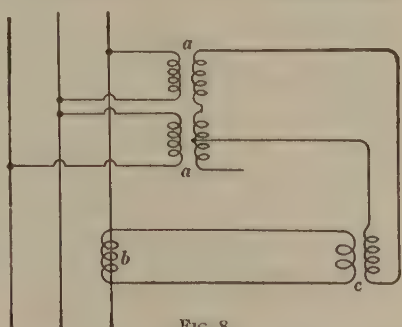


FIG. 8

In order to save expense by using two pressure transformers instead of three, a pressure in phase with star pressure but having a value one and one-half times as great is sometimes

used. This is secured by connecting two potential transformers open-delta, or **V**, and connecting the instrument circuit from the outside secondary terminal of one to the middle of the secondary winding of the other, as shown in Fig. 8. Multiply the instrument reading by two.

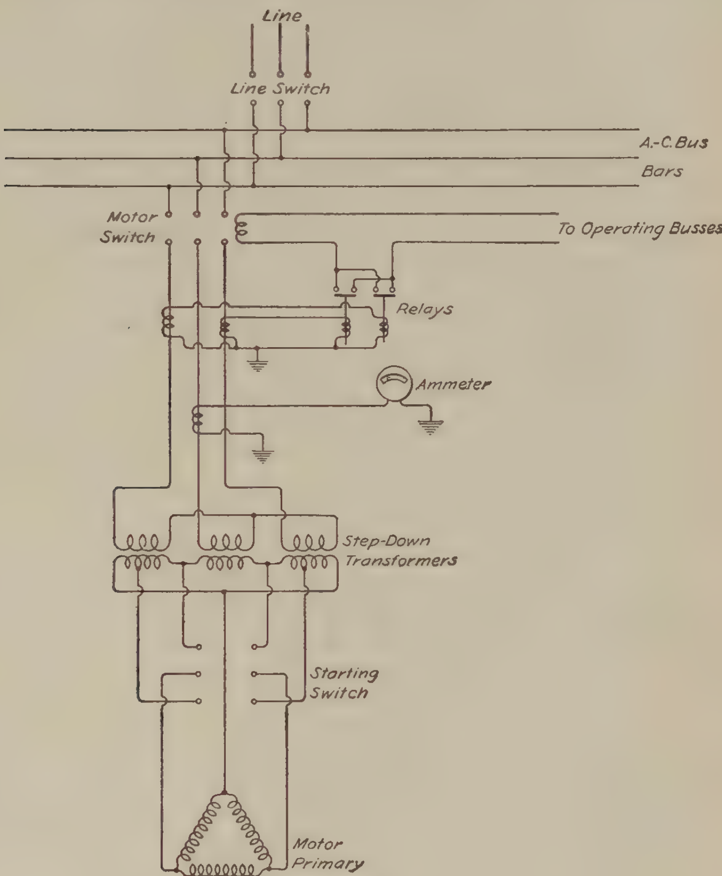


FIG. 9

Watt-hour meter connections can also be made as in Figs. 5 and 6 and watt-meter connections as in Figs. 7 and 8. Polyphase instruments connected as described in *Watt-Hour Meters* can also be used.

WIRING DIAGRAMS

35. In Fig. 9 is shown a wiring diagram of a three-phase induction motor connected to step-down transformers and in Fig. 10, a diagram of a three-phase motor operating on full

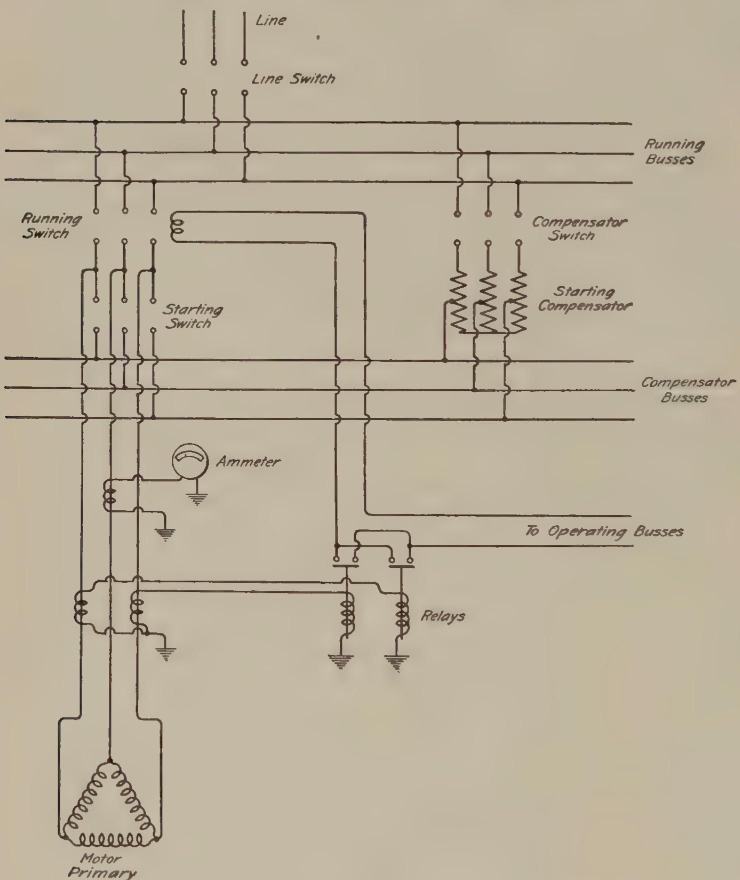


FIG. 10

line potential. These two illustrations show the relations to one another of the details given in Figs. 3 to 6; in Figs. 9 and 10, no wattmeter nor watt-hour meter connections are included.

MOTOR-GENERATOR SUBSTATIONS WITH SYNCHRONOUS MOTORS

MISCELLANEOUS EQUIPMENT

36. Synchronous motors, because of their ability to improve the power factor of the system, are sometimes preferred to induction motors for driving substation generators. They are manufactured for operation on circuits with pressures considerably higher than generally applied directly to induction motors.

In the selection of transformers and cooling apparatus the same considerations apply to synchronous-motor installations as to induction-motor substations; but, as the power factor of a synchronous motor can be made 100 per cent., the transformers may have a somewhat smaller rating in kilovolt-amperes than those to be used with induction motors.

The high-tension bus and oil-switch equipment for a synchronous-motor-generator substation is the same as for an induction-motor installation, as are also the current transformers, potential transformers, and overload relays. In addition to the measuring instruments mentioned in connection with induction-motor installations, a power-factor indicator may be used in connection with synchronous motors, although its use is a convenience and not a necessity; an alternating-current ammeter in one phase is more needed.

METHODS OF FIELD EXCITATION

37. Excitation From Main Generators.—Direct current for exciting the field of a synchronous motor in a substation may be supplied from a separate exciter unit or from the generator of the motor-generator set, provided that the generator is compound wound and delivers direct current at the proper pressure for excitation.

When the second method is used, the exciting circuit may be taken either from the load busses or from the machine leads.

If the generators are protected by circuit-breakers in the armature leads, the exciting circuit is not taken from the load busses, because the opening of all the circuit-breakers would cut off the supply to the direct-current busses and thereby "kill" all the fields. As a result, the synchronous motors would likely fall out of phase and automatically open the oil switches, thus shutting down the substation. For this reason, each motor should have its field leads connected to the armature leads of the generator that it drives, and the connection should be made on the armature side of the circuit-breakers and knife-blade switches as shown in Fig. 11, which is a simple diagram of the connections of a railway unit.

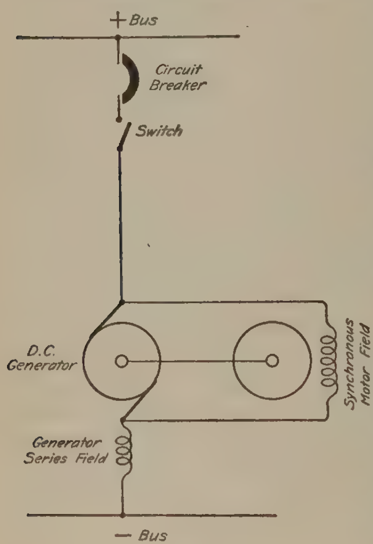


FIG. 11

38. Excitation From Separate Unit.—If the main direct-current generator is shunt wound, there is some danger in using current from it for excitation purposes, as a severe short circuit on the direct-current circuit may cause the generator to lose its voltage. This would result in killing the fields of the synchronous motor, thereby causing the motor to fall out of phase. In such cases a special exciter set is safer and is generally used, though excitation by a special generator is less reliable than from the main generator leads of a compound-wound generator.

Special exciters, when used, should be installed in duplicate, as an accident to one cannot then result in shutting down the entire substation. On account of the expense of separate exciters, it is the common practice to install exciters with enough capacity to supply the fields of several or all of the main units and to connect them to special exciting busses.

Generators for exciting purposes need not be compound wound, as the load on the exciter generators is not changed except by the operator, who is then at the switchboard and at hand to regulate the pressure of the exciting busses. A separate exciter generator may be driven either from an extension of the shaft of the motor-generator or by a special induction motor.

STARTING

39. Some synchronous-motor-driven generator sets supplying direct current are used in service where it is particularly undesirable to use alternating current for starting, on account

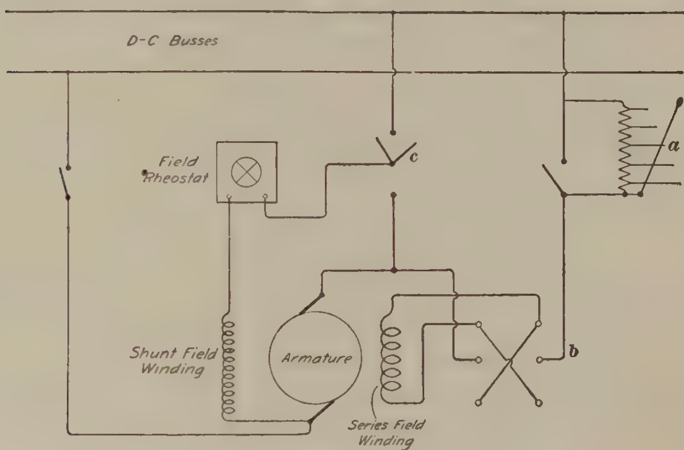


FIG. 12

of the fluctuations in line pressure resulting from the heavy flow of starting current. These can be provided with equipment for starting with direct current, if it is always available. In this case the generator becomes, for starting purposes, a direct-current motor, and the synchronous motor acts as an alternating-current generator until synchronized to the alternating-current supply. This requires the installation of a starting resistance and starting switch *a*, Fig. 12, in the armature circuit of the direct-current generator. If the direct-current generator is compound wound, a reversing switch *b* is generally

provided for reversing the series field, in order to permit the operation of the machine as an accumulatively wound motor. To permit excitation from the machine leads during normal operation, but to provide means for excitation from the busses while starting, a split switch *c* is inserted in the shunt-field circuit. After the machine is started and the starting resistance is entirely out of circuit, the split-blade switch is used to transfer the field circuit from the busses to the machine leads. The transfer is accomplished without opening the field circuit.

The alternating-current circuits are not shown in Fig. 12. Direct-current starting, however, does not require any special alternating-current connections except that a potential transformer must be connected to one phase of the synchronous-motor armature leads to provide pressure for a synchronizing circuit.

SYNCHRONOUS-CONVERTER SUBSTATIONS FOR RAILWAYS

TYPES AND CAPACITIES OF CONVERTERS

40. Nearly all synchronous converters used in railway service are compound wound, in order that the voltage regulation may be partly automatic; because the load of a railway substation is extremely variable, and continuous attention at the switchboard would be required if shunt-wound machines were used. A compound-wound synchronous converter, if provided with a series reactance in the transformer secondary circuit, automatically regulates the potential for some distant point on the railway system.

In some cases where storage batteries are floated in parallel with synchronous converters, the compound winding has either been cut out of circuit, or shunted with a heavy copper bar, in order to avoid the unsatisfactory features of regulation that result from operating in parallel two sources of electric energy with unlike characteristics. The operation of shunt-wound synchronous converters in railway service results in poor pressure regulation on the feeder system and is seldom resorted to.

If the service is such as to require that a battery be floated on the busses, a differentially compounded booster is sometimes used in series with the battery, and the battery, with its booster, is operated in parallel with the compound-wound rotary converter.

41. The capacities of the substation units, if there are more than one, are generally so chosen that the operation of a large machine for a very small load will not be necessary. It is, of course, desirable to have more than one unit, because any disability that puts the only machine in a substation out of service results in interrupting the entire supply of the substation.

HIGH-TENSION CONSTRUCTION

42. The high-tension bus and oil-switch construction of synchronous-converter substations is made as simple and accessible as possible. If the transmission line voltage is higher than about 5,500 and lower than about 30,000, the cellular and barrier type of construction is used for the proper separation of the phase conductors after they have entered the building, or been brought out of the terminal bell of the transmission line cable.

MAIN ALTERNATING-CURRENT CONNECTIONS

43. Connection Diagram of Six-Phase Synchronous Converter.—In Fig. 13 is shown a wiring diagram of a six-phase synchronous converter that receives starting current from sectional taps on the secondary windings of the step-down transformers. The primaries of the transformers are connected **Y**; the secondaries are diametrically connected to the armature. The wiring of the converter is such that opposite terminals of each diametrical circuit connect to points in the armature winding 180 electrical space-degrees apart. Because of the **Y** connection, only .577 of the full transmission-line pressure is impressed on the primary terminals of each transformer—a desirable condition when the line voltage is 20,000 or greater.

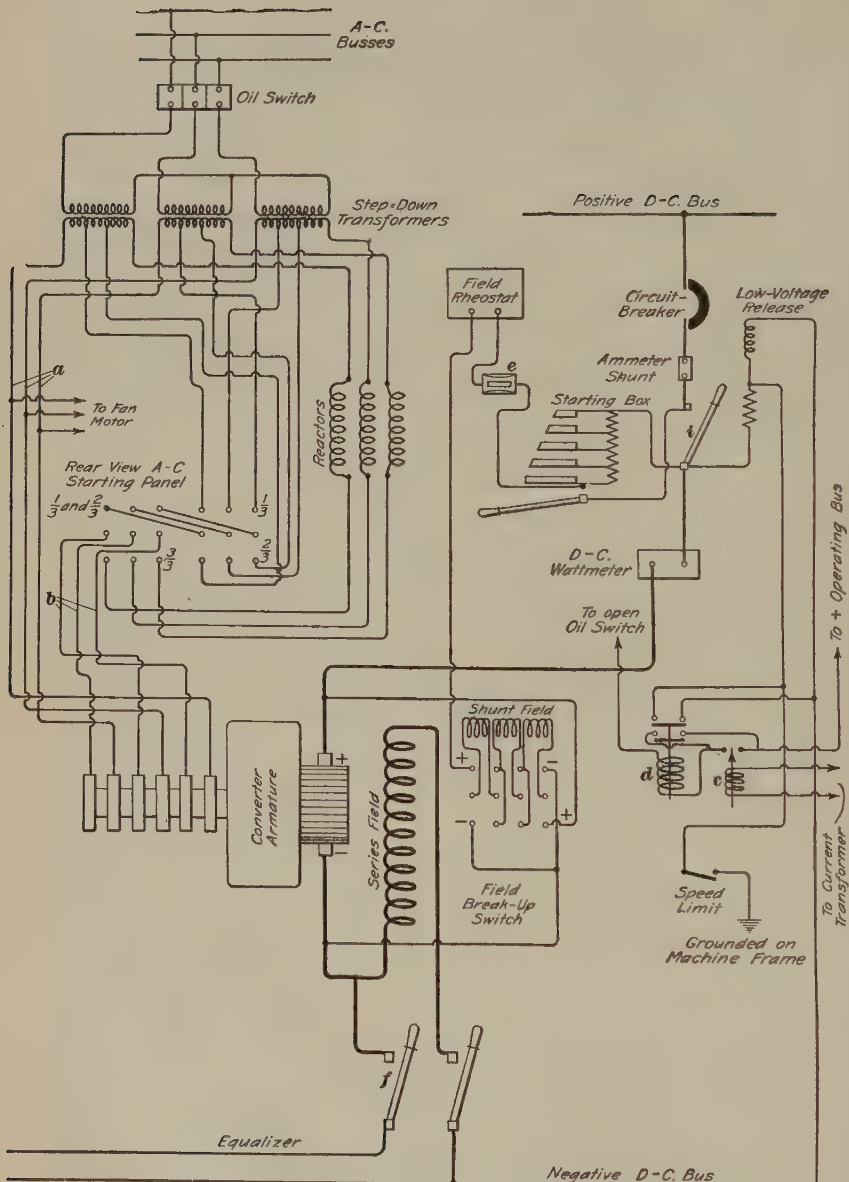

A-C. Busses
Oil Switch
Step-Down Transformers
Positive D-C. Bus
Field Rheostat
Circuit-Breaker
Low-Voltage Release
Ammeter Shunt
e
Starting Box
i
a
To Fan Motor
Reactors
Rear View A-C Starting Panel
1/3 and 2/3
1/3
2/3
3/3
D-C. Wattmeter
To open Oil Switch
To + Operating Bus
b
Shunt Field
d
c
Converter Armature
Series Field
Field Break-Up Switch
Speed Limit
To Current Transformer
Grounded on Machine Frame
f
Equalizer
Negative D-C. Bus

FIG. 13

In order that the compound winding of the synchronous converter may be effective in performing automatic regulation of the direct-current pressure, a reactance is inserted in series with the secondary leads between the transformer terminals and the collector rings. These reactances may be self-cooling, but are generally supplied with air from the air-blast system if air-cooled transformers are used in the installation.

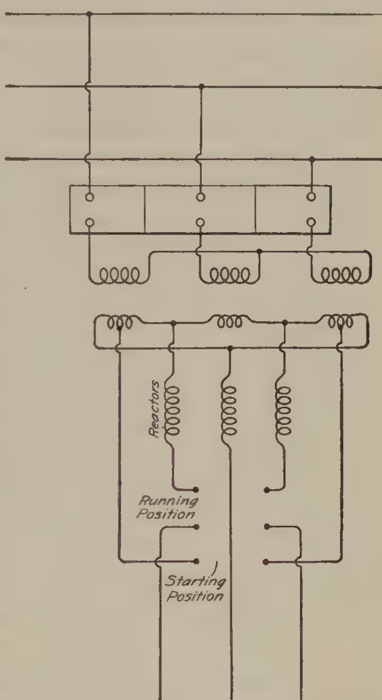


FIG. 14

44. Connection Diagram of Three-Phase Synchronous Converter.—On account of the superior efficiency of six-phase synchronous converters, the three-phase type is not very desirable. Fig. 14 shows the general arrangement of the wiring of the alternating-current side of a three-phase synchronous converter with delta-connected transformer secondaries. With the exception of the secondary connections, the arrangement is essentially the same as that of the six-phase unit. The direct-current connections of the two types of units are identical.

STARTING SYSTEMS

45. The alternating-current starting-switch connections of the six-phase synchronous converter, Fig. 13, are so arranged that either one-third or two-thirds of normal secondary voltage can be obtained for starting and accelerating the armature and full voltage for regular operation. Switches for starting large units are provided with carbon-break contacts.

46. Some synchronous converters are provided with induction motors for starting and accelerating the armatures. The induction motors may be supplied either from the secondaries of the transformers supplying the converters, or from a special bank of transformers used for supplying starting currents for all the units.

47. In some installations, each synchronous converter is provided with a starting-box resistance, as shown in Fig. 13, connected in the direct-current leads so that the converter can be started with direct current like a direct-current motor. Fluctuations of direct-current voltage cause variations in the speed of the motorized converter; hence, direct current from railway circuits is not convenient to synchronize railway synchronous converters. The more general practice is to get them up to speed, disconnect them entirely from the direct-current busses, and then close the alternating-current switches.

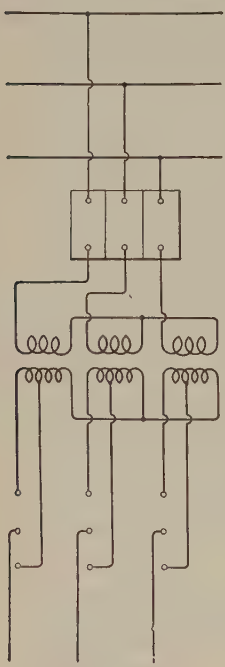


FIG. 15

48. In the three-phase installation shown in Fig. 14 the starting switch is double pole, double throw. Two of the starting pressures are taken from the middle points of two of the transformer secondaries and the third phase may be permanently connected. The running position of the double-throw starting switch is such that it connects the machine to the full-pressure terminals of the transformer. In order to secure this simple arrangement of starting circuits, the transformer secondaries are connected delta. When the star connected secondaries are used, it is necessary to use a three-pole double-throw switch connected as shown in Fig. 15. The motor is entirely disconnected from the transformer when the switch is open.

SHUNT-FIELD CONNECTIONS

49. In order that the field rheostat may be situated at or near the switchboard, the positive side of the shunt-field winding of a synchronous converter is connected to the positive armature lead at the switchboard; and, in order that the field may be properly excited whenever the machine is in operation, even though the circuit-breaker or the main positive switch *i*, Fig. 13, is open, the connection is made on the armature side of the knife-blade switch, as shown. The connection between the rheostat and the field is made by a wire or small cable that connects to the reversing field-break-up switch.

The negative terminal of the shunt field is connected to the negative lead of the armature on the armature side of the compound winding (short shunt), but it may be on the ground side (long shunt). In operation, one form of shunt connection is as good as the other, but the short shunt has the advantage of having fewer joints in the circuit, reducing the liability of an accidental opening of the shunt-field circuit.

50. The reversing field-break-up switch is provided for sectionalizing the shunt-field circuit when starting the machine with alternating current and for correcting the polarity of the machine, if it is incorrect at synchronous speed.

Sectionalization of the shunt field during starting is necessary, because when alternating current is applied to the armature when at rest or when running non-synchronously, the armature winding acts as the primary of a transformer of which the shunt-field winding is the secondary. The number of turns in the armature winding is small and the total number of turns in the shunt-field winding is quite large; therefore, if the entire shunt winding is connected, the secondary electromotive force induced may be sufficient to puncture the insulation of a field winding, or leads, and cause a breakdown. If, however, the shunt winding is sectionalized by opening the field-break-up switch, each section becomes a secondary with a much smaller number of turns, and the electromotive force induced is so small as not to be dangerous.

When starting a synchronous converter from the alternating-current side, the magnetic flux in the pole pieces is alternating until the armature reaches synchronous speed. With this method of starting, therefore, the polarity at synchronous speed is liable to be incorrect for direct-current operation. Before connecting in the shunt field, a voltmeter test is made for polarity, which, if incorrect, is reversed by momentarily throwing the field-break-up switch to the reverse position, the lower position in Fig. 13, then opening it and repeating the test. When the polarity is correct, the field switch is closed in its operating position.

EQUALIZER CONNECTIONS

51. The wiring diagram, Fig. 13, shows the rotary converter compounded and equalized on the negative, or grounded, side, which is the most common form of installation. The practice of compounding and equalizing on the grounded side has the advantage of making the equalizer switch *f*, which is usually on the machine frame, or on a small panel near it, at ground potential, and of confining to the switchboard all of the armature-circuit switches having potentials above that of the ground. The equalizer switch is placed at or near the machine instead of on the switchboard, in order to make the equalizer connection as short as possible and, therefore, to make its resistance low in comparison with that of the series fields, a condition necessary to good equalization.

52. The amount of compounding of a synchronous converter is adjusted by means of a shunt, generally of German silver, connected in parallel with the series-field winding. If the machines are alike in size, design, and characteristics, they may usually be adjusted to work well in parallel and properly divide the load in proportion to their capacities by suitably proportioning the relative resistances of their series fields and series-field shunts. If, however, they are unlike in these respects, some difficulty may be experienced in making the machines divide the load properly. The fields of a large machine may respond to changes in the series current more slowly than those of the smaller ones, and the same trouble

is experienced as with compound-wound generators. It is useless to attempt to effect any considerable change of load distribution between units by adjusting the shunts of the series fields. Though this method effectually controls the compounding of a single unit, the shunts of two machines in parallel are, in effect, equal to one shunt in parallel with both series fields. The shunts control the compounding effect of the two machines with respect to the load, but not with respect to each other. The only method of properly adjusting the load division is by a suitable adjustment of the relative resistances of the parallel paths between the equalizer circuit and the direct-current bus of the same polarity, each path including a series field.

AUXILIARY-MOTOR CONNECTIONS

53. A fan supplying air for cooling transformers in a direct-current railway substation can be driven by a motor taking direct current from the railway bus, or by an induction motor supplied with current from the secondary of the transformers of one of the converter units, the latter method being the more general practice. A direct-current motor stops whenever the bus is killed by the automatic operation of all of the machine circuit-breakers and must be started after each interruption. This difficulty is sometimes obviated by having a small power bus receiving its supply from the machine leads on the machine side of the knife-blade switches a, Fig. 16. By a selective system of switches b current for the auxiliary-power supply can be taken from any machine. However, the scheme shown in

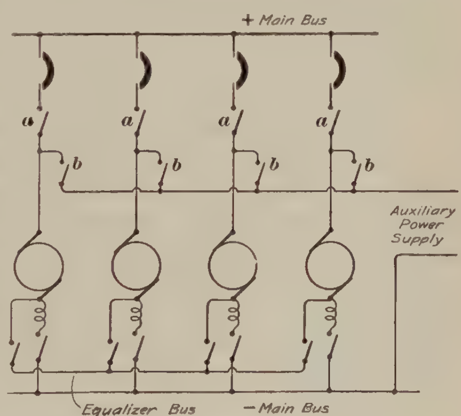


FIG. 16

Fig. 16 introduces the liability of operating errors; induction motors are cheaper and more reliable.

54. Induction motors for air-blast fans are three-phase and are wound for operation on the three-phase secondary voltage, usually about 360 volts, of the synchronous converters. For these motors, there are two forms of starting equipment. One form consists of a double-throw switch; one side has no fuses in circuit and is used for starting the motor at full potential, and the other side has fuses that are in circuit during normal operation. The switch should be connected to the three transformer leads *a*, Fig. 13, that go directly to the armature collector rings, or else to the leads *b* on the machine side of the secondary starting switches in preference to those on the transformer side. With either of these connections, it is impossible to operate the fan motor when the synchronous-converter armature is at rest, even though the transformer may be alive.

55. If the substation transformers are oil-and-water cooled, a small motor is sometimes required for operating the pump to circulate water through the cooling coils. This motor is connected in the same manner as the motor for driving the air-blast fans.

INSTRUMENT, RELAY, AND PROTECTIVE-DEVICE CONNECTIONS

56. Instrument and Relay Connections.—The instrument connections on the direct-current end of a synchronous converter are the same as for a direct-current railway generator. The alternating-current end of the unit has overload relays, alternating-current ammeter, power-factor indicator, and, sometimes, an alternating-current wattmeter.

With respect to the connection of overload relays there is no fixed practice. Some installations are made with three overload relays supplied from three current transformers, one of which supplies current to the alternating-current instruments also. In other installations, one current transformer supplies the ammeter, one supplies the power-factor indicator, and a third the wattmeter, and each supplies one overload relay.

One side of the secondary of each current transformer is connected to a common ground, usually a ground plate, to which is connected the ground return of all the instruments. The other terminals of the current transformers connect the instruments and relays; the remaining terminals of the instruments and relays are connected to a small ground bus that leads to the ground plate.

Current transformers are most satisfactory when working with very little resistance in their secondary circuits, and for this reason some installations are made with one current transformer for the instruments and two for the overload relays, as shown in Fig. 17. This form of connection is suitable for installations in which the transformer primaries are delta connected, but is not generally used with star-connected transformer primary windings, where it is desirable to have overload protection on each phase separately.

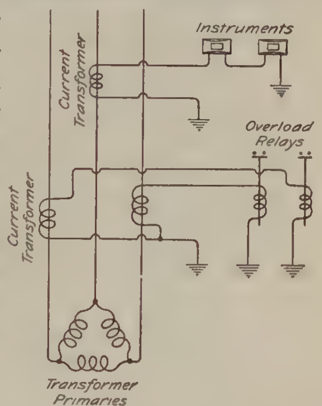


FIG. 17

Current transformers are inserted in the primary circuit between the oil switch and the transformers and as near to the oil switch as is convenient.

57. An alternating-current relay *c*, Fig. 13, can be arranged to close the operating circuit through the solenoid of a second relay *d* with two contactors, one of which short circuits the low-voltage release coil of the direct-current circuit-breaker. The other contactor short circuits the contact points of the relay *c*, thus completing a circuit through the solenoid of the relay *d*, electrically locking it in the closed position, regardless of the position of the alternating-current relay *c*, and insuring the opening of the oil switch.

An ammeter *e* is usually connected in the field circuit of a synchronous converter.

58. Operating-Bus Supply.—A supply of direct current for operating the substation oil switches is sometimes taken

from the direct-current railway bus. This practice is not common, because oil-switch operating devices are generally wound for 110 to 125 volts and it is difficult to obtain good results by deriving the supply for their operation from 550- or 600-volt circuits.

The supply can be obtained from the railway bus by either of two methods. In one method, a fixed resistance is inserted in series with the supply to the operating circuits to reduce the potential drop across the windings of the operating devices to about 125 volts. This method is objectionable for two reasons: It causes the cut-out devices in the operating circuits of the oil switches to break a heavy arc at practically the full potential of the railway circuit and results in serious burning of the contacts. In addition, the resistance, though correct for giving the proper voltage when supplying 15 or 20 amperes for operating a switch, is too little for cutting down the pressure for the pilot lamps of the oil-switch circuits. Another method is to use a resistance through which a current passes continuously and to tap the resistance at such a point as to obtain 125 volts for the operation of oil switches and pilot lamps. The operating devices and pilot lamps then become paths in parallel with a part of the resistance.

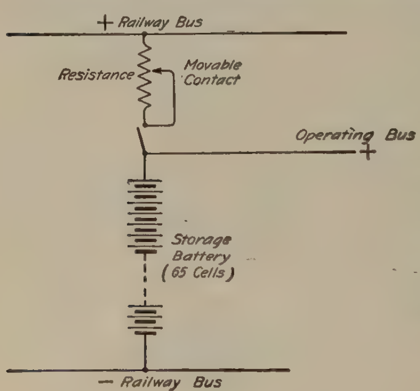


FIG. 18

Both of the methods just explained are objectionable in operation and both have the serious defect of being inoperative when the substation is shut down, because there is then no supply of current to operate oil switches to start the substation machinery. It is more general practice to install a small storage battery of about sixty-five cells and having a capacity of 20 to 40 amperes. The battery is charged from the 550- or 600-volt railway bus with a resistance in series, as shown in

Fig. 18, or, in some installations, by means of a mercury-arc rectifier.

59. Lightning Protection.—If the ratio of transformation of the step-down transformers of a substation is large, there may occur on the secondary circuits momentary voltages greatly in excess of the normal potential and sufficient, under certain conditions, to cause a puncture of insulation between conductors and the armature core or other grounded parts of the converter and thus to present a path for the large currents, which may have very destructive effects. These so-called *static disturbances* are reduced in extent by connecting a small aluminum cell lightning arrester across the direct-current terminals of the synchronous converters.

60. Speed-Limit Device.—In order to protect a synchronous converter against the possible destructive effects of overspeeding—which sometimes occurs if the alternating-current supply is interrupted and the machine back-feeds into a line short circuit, or which is certain to occur if the field circuit is opened when the machine is running as a direct-current motor—a speed-limit device is used to open automatically the circuit-breaker when the speed reaches a predetermined value. The circuit-breaker is opened by the short circuiting of its low-voltage release coil by a centrifugal device on the shaft. The speed-limit device is usually adjusted to open the armature circuit when the speed is about 15 or 20 per cent. above normal.

61. Reverse-Current Protection.—When a synchronous converter is operated in parallel with a storage battery, either with or without a booster in series with the battery, it is desirable to install reverse-current protection to prevent the machine from inverting from the battery into a line short circuit.

Reverse-current relays are made in different forms. One form in general use on railway systems is actuated by the magnetic field that surrounds the machine lead and makes a contact that operates a relay. The contacts of the relay are so connected as to short-circuit the low-voltage release coil of the circuit-breaker and thus to cause the circuit-breaker to open.

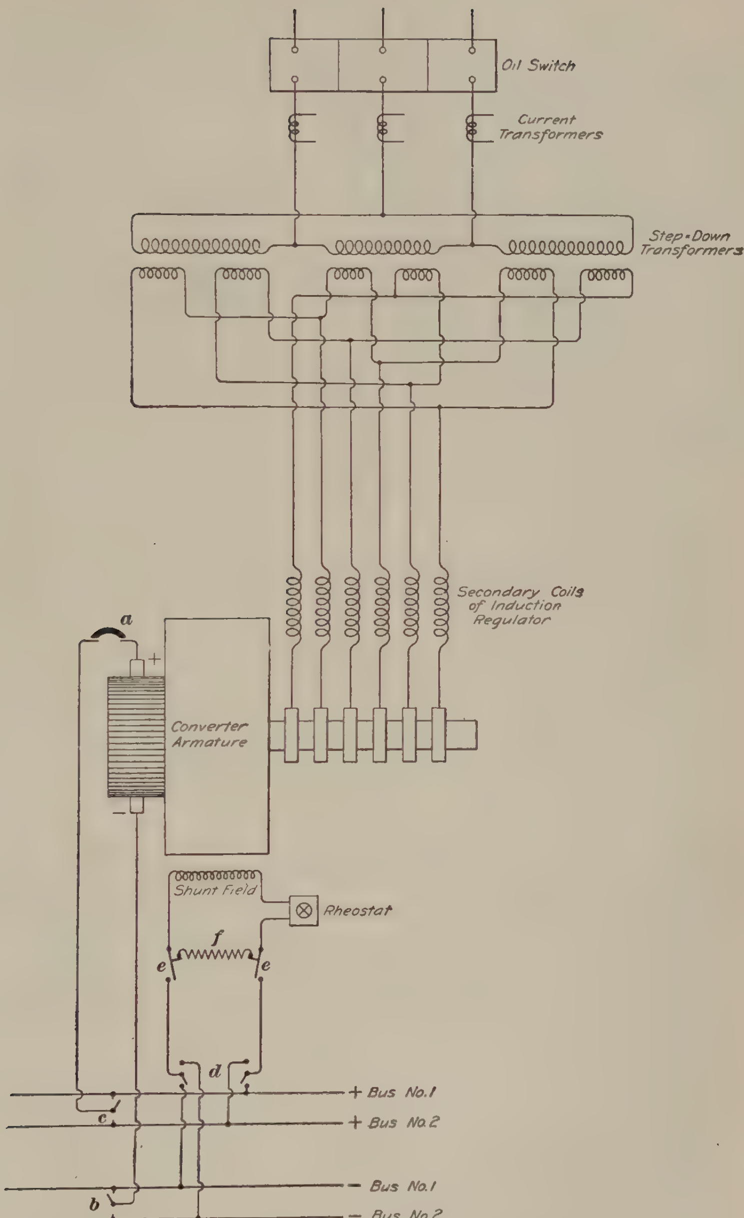
PORTABLE SUBSTATIONS

62. On large railway systems, even though the distribution system was originally designed of ample proportions to meet all normal conditions, events are likely to occur that attract unusual travel in certain directions at irregular intervals. A special attraction at any point may necessitate running, for a short period, many cars on a branch that ordinarily handles but two or three. The system must be prepared to meet these extra demands; but the installation of sufficient capacity in feeders and substations necessitates an investment that, during a large portion of the time, yields no return. In order to meet these temporarily heavy demands with the least expense, a certain flexibility of distributing system is demanded, so that the increased capacity may be easily and quickly moved from one line to another as the conditions may demand. On a number of systems this flexibility has been attained by the use of portable substations. Practically the same apparatus as is used in a permanent substation is assembled in a specially arranged car having very much the appearance of an ordinary freight car. This car can be hauled to any place to which the high-tension lines have been extended, run on a siding, connected up, and put into service in a very short time.

SYNCHRONOUS-CONVERTER STATIONS FOR LIGHT AND POWER

FUNDAMENTAL SYSTEMS OF CONNECTION

63. Synchronous-converter substations for general light and power commonly supply three-wire systems operating at about 110 to 125 or 220 to 250 volts. In many cases Edison three-wire systems are supplied, and 220- to 250-volt machines are connected to the two outside conductors of the system with a derived-neutral connection to the neutral conductor of the three-wire system. In some cases, two synchronous converters delivering voltages of from 110 to 125 are connected



Oil Switch
Current Transformers
Step-Down Transformers
Secondary Coils of Induction Regulator
a
+
Converter Armature
−
Shunt Field
Rheostat
f
e
e
d
+ Bus No.1
c
+ Bus No.2
− Bus No.1
b
− Bus No.2

FIG. 19

to the three-wire system in the same manner as a pair of 110-volt generators. In other cases, a 250-volt converter is arranged to feed into the two outside conductors of the three-wire system, with the neutral in no way connected to the converter armature, as in Fig. 19, which shows the main connections for a six-phase shunt-wound machine.

64. Main Connections.—The installation shown in Fig. 19 is of a form in quite general use. Having no neutral connections, the unit is unable to supply an unbalanced load. Any unbalancing must be carried by a balancer set or by a storage battery.

In Fig. 19 the transformer primaries are shown connected delta, although this is not essential; if the installation were to operate on very high voltage, star connection would be used. The secondary connections shown are double-delta, six-phase, the six-phase relation being obtained by dividing the secondary windings of each transformer into two equal and independent parts, connecting the first in delta and the second in a delta reversed with respect to the first. With this arrangement there are two separate secondary deltas out of phase with each other by 180°. These connect through a six-phase induction-type potential regulator to the collector rings of the synchronous converter.

The synchronous-converter armature is connected to the direct-current bus through a circuit-breaker *a* in one lead, either positive or negative, and a knife-blade switch in each lead. When a duplicate direct-current bus system is installed, as shown, the knife-blade switches *b* and *c* are double-throw, in order that the machine can be connected to either set of busses.

The positive lead of the machine has a tap to which a starting circuit, not shown in Fig. 19, is connected for starting the converter as a direct-current motor. One starting bus and one starting resistance may be used to start all of the machines in the substation.

The connections of the three-phase delta-connected system are very similar to those shown in Fig. 14. Like the six-phase

double-delta connections, they cannot be used for supplying a derived neutral.

65. Protective Devices.—The circuit-breaker *a*, Fig. 19, is installed to open the armature circuit in the event of excessive speed of the machine and to disconnect the machine if the current reverses in direction in a predetermined amount. The reverse-current feature is sometimes omitted, as it has been found that the machine is thereby occasionally disconnected from the direct-current bus at times when the continuity of service should be preserved. The circuit-breaker is sometimes, though less frequently, used to disconnect the unit from the bus in the event of a severe overload.

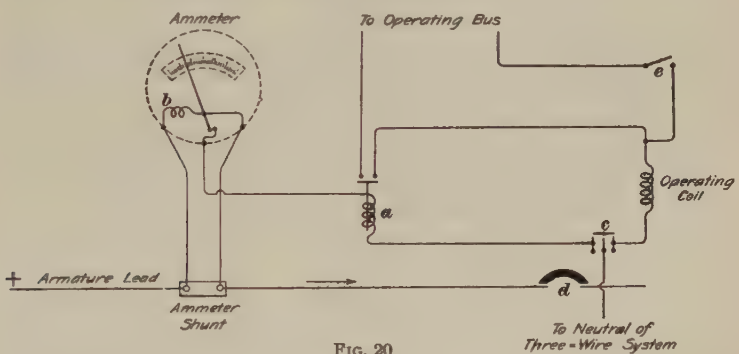


FIG. 20

In Fig. 20 are shown the essential connections of the operating circuit of the circuit-breaker. The coil of the reverse-current relay *a* is energized from a special connection so situated inside the ammeter case as to make contact with the counterbalance of the needle when the pointer is in a position for indicating a reversal of current in a predetermined amount. When this contact is made, current passes through the armature coil *b* of the instrument, holding the needle firmly in position against the relay connection, thus perfecting the contact, and then passes through the relay coil *a* and through an auxiliary switch *c* on the circuit-breaker *d*. The auxiliary switch opens the relay circuit as soon as the circuit-breaker opens, and thus protects the winding of the relay coil and the armature coil of

the ammeter from a continuation of the comparatively heavy current that passes during the brief time required for opening the circuit-breaker.

The circuit closed by the speed-limit device *e* is connected

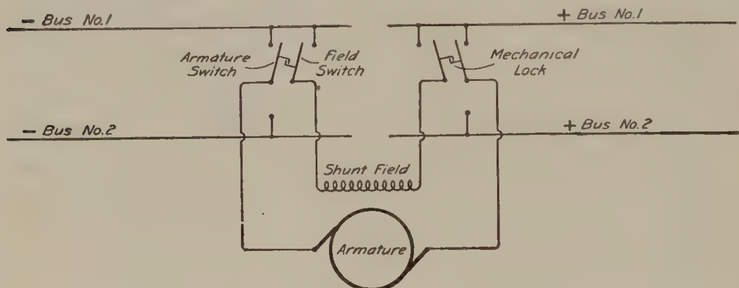


FIG. 21

between the operating bus, or the load bus, and the operating coil of the circuit-breaker. This system of speed-limit protection differs slightly from that shown in Fig. 13, in which the speed-limit device short-circuits the low-voltage release.

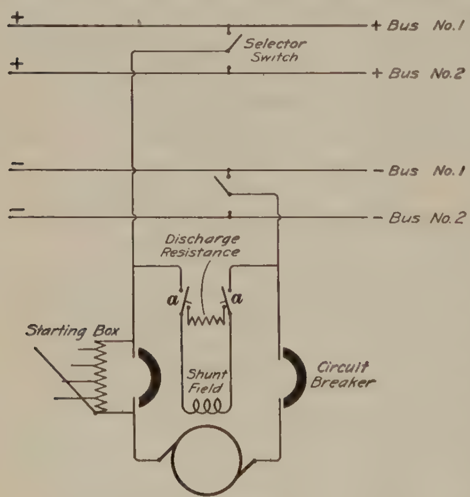


FIG. 22

66. Shunt-Field Connections.—The shunt-field circuit, Fig. 19, can be connected to either of the duplicate load busses by means of double-throw selector switches *d*. In addition, quick-break switches *e* and a field discharge resistance *f* are provided.

In Fig. 21 is shown a connection by which a synchronous converter can be excited from the load bus for starting and by which, after starting, the field switches are mechanically locked and electrically connected to the knife-blade switches of the

armature. After the machine is synchronized and the field switches are locked and connected to the blades of the armature switches, the armature switches can be opened, if necessary, and the field circuit will remain excited from the machine leads. The unit is provided with double-throw switches for selective connection between two direct-current busses and may be transferred from one bus to another without the danger of killing its field circuit.

In Fig. 22 is shown a simpler scheme by which the field circuit is connected through quick-break switches *a* to the machine leads. This arrangement also permits self-excitation while transferring the unit between busses. When this form of connection is used, the starting resistance is connected across one of the circuit-breakers, in order that the synchronous converter may have full-field excitation when the starting resistance is in circuit.

THREE-WIRE SYSTEMS WITH DERIVED NEUTRAL

67. Methods of Deriving Neutral.—In Fig. 23 is shown a wiring diagram of a six-phase, 250-volt, synchronous converter with diametrically connected (double-star) transformer secondary windings and a derived neutral. This arrangement is superior to the one shown in Fig. 19, as the middle points of the diametrical winding afford a source of neutral potential. As the secondary of each transformer, Fig. 23, is connected across the armature to points 180 electrical space-degrees apart, the potential of the middle of the secondary winding is midway between that of each of the outside terminals of the armature. This is the potential of the neutral conductor of a properly balanced three-wire system. Since the middle points of each of the three diametricals are of the same potential, they are connected to the neutral of the three-wire system, and the synchronous converter is able to supply current to an unbalanced load. The neutral current then passes back through the neutral connections of the transformer secondary.

A switch *a*, Fig. 23, is installed in the neutral lead, in order that the neutral circuit may be opened when the machine is to be started with direct current. Assuming the starting

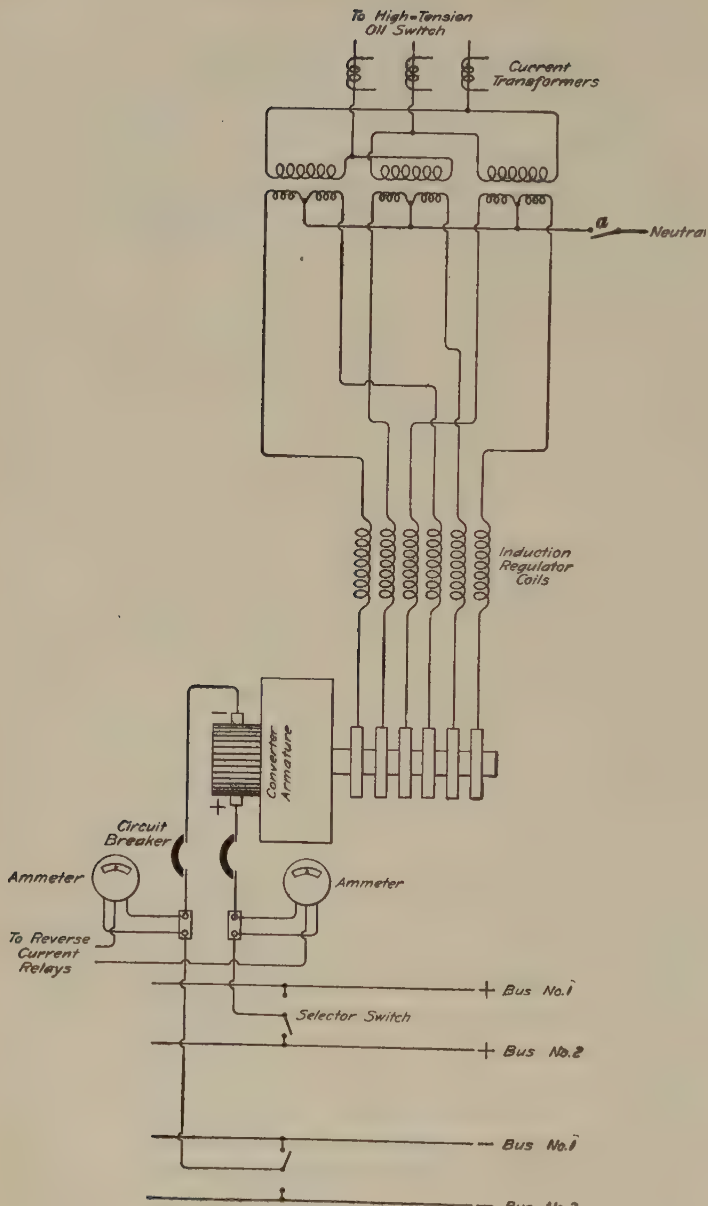

To High-Tension
Oil Switch
Current
Transformers
a
Neutral
Induction
Regulator
Coils
Converter
Armature
Circuit
Breaker
Ammeter
Ammeter
To Reverse
Current
Relays
+ Bus No.1
Selector Switch
+ Bus No.2
— Bus No.1
— Bus No.2

FIG. 23

resistance to be in the positive lead, the negative switch should not be closed when the neutral switch is closed and the armature is at rest. The other machines would then send current from the neutral of the system, through the synchronous-converter armature, through one-half the transformer secondaries, to the negative bus. This path is one of very low resistance and would constitute a short circuit on the negative side of the three-wire system.

68. When taps from the middle points of the transformer secondaries are not available, a derived neutral is sometimes obtained by connecting a suitable reactance, or one winding of a transformer, across two properly selected secondary leads and connecting the middle point of this reactance or winding to the neutral of the three-wire system. The other winding of the transformer so used is left open-circuited and inactive. A reactance serves the purpose as well as a transformer,

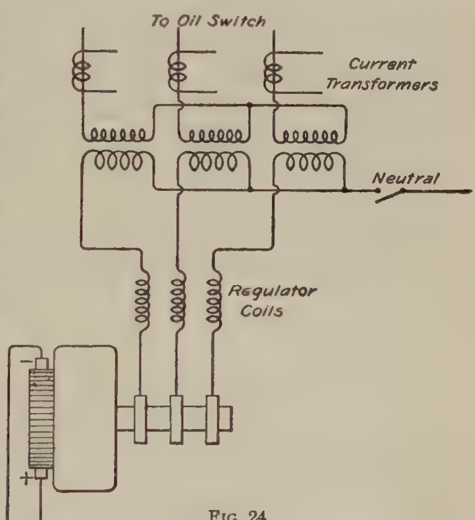


FIG. 24

and, being considerably cheaper, is generally used in preference to the transformer. The transformer coil or the reactance coil, as the case may be, must be connected to points of the armature 180 electrical degrees apart, as, for example, to collector rings No. 1 and No. 4, to No. 2 and No. 5, or to No. 3 and No. 6.

69. Another form of derived neutral connection for a six-phase machine is made by the use of three transformer windings or reactances connected in star, with the neutral point connected to the neutral of the three-wire system and the other three terminals connected to points in the armature winding

120 electrical degrees apart; that is, in this case to alternate collector rings, as, for example, Nos. 1, 3, and 5 or Nos. 2, 4, and 6.

The method of deriving a neutral from star-connected transformer secondaries for a three-phase machine is shown in Fig. 24.

70. Miscellaneous Connections.—A synchronous converter with a derived neutral and with one side, either positive or negative, connected to the neutral can be operated as a two-wire unit with a rather limited capacity. The machine can also be motorized through a circuit consisting of the neutral connection and either the positive or negative lead. Therefore, when the neutral switch is closed, the armature circuit is not completely opened unless both positive and negative conductors are open-circuited. For this reason two circuit-breakers, as shown in Fig. 23, are necessary in connection with the unit having a derived neutral. The operating coils (not shown) of the circuit-breakers are connected in parallel.

Ammeter, relay, and shunt-field connections are the same as those described in connection with Figs. 19 to 22, inclusive.

TWO CONVERTERS SUPPLIED FROM ONE BANK OF TRANSFORMERS

71. Two synchronous converters for operation on three-wire systems are sometimes connected to one bank of transformers. When this is done, the transformer secondaries may be wound for supplying 77 volts, three phase, to the machines, which are connected in parallel to the transformer secondary terminals. Another form of connection has each secondary divided into two parts; each part supplies 77 volts, and one unit is connected to each set of secondaries, as shown in Fig. 25. Since both of the converters are supplied from one set of transformers, the primary oil switch of the set cannot be satisfactorily used for synchronizing, and it is therefore necessary to use secondary switches, not indicated in Fig. 25, in the leads to each rotary converter. The practice of synchronizing with secondary switches is not uncommon, even in connection with

large units, and there are in regular operation many rotary converter installations of large capacity that are synchronized

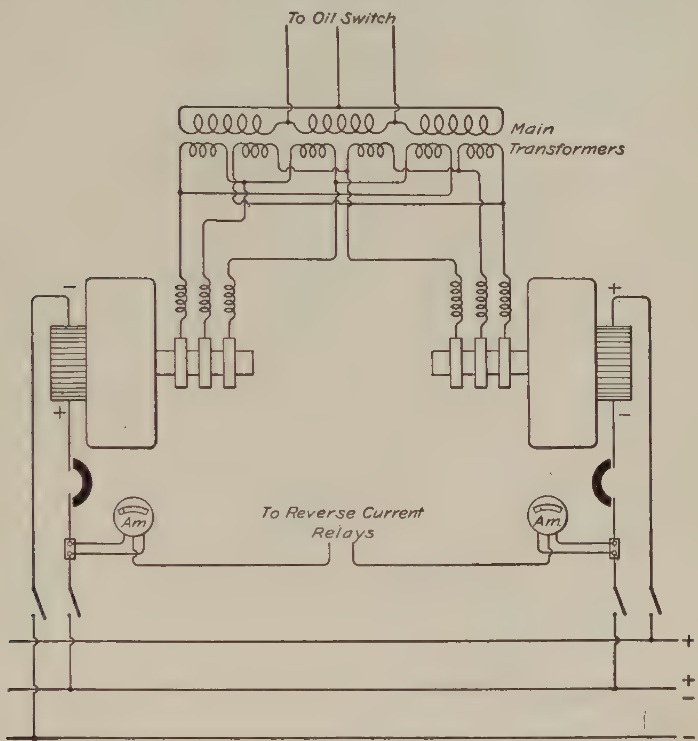


FIG. 25

to the transformer secondaries by means of heavy secondary switches, some of which are adapted for remote control.

STARTING

72. Starting With Alternating Current.—Synchronous converters used in lighting and power work and having six-phase diametrically connected transformers can be started with alternating current by using the same form of starting connections as those used on railway machines. The starting connections,

however, require some special arrangement when used with units with derived neutrals, as it is necessary to provide for separating the neutral connections to the transformer secondaries during starting. Fig. 26 shows the arrangement of the secondary circuits of a rotary-converter unit for starting with one-half the normal secondary voltage. The neutral point

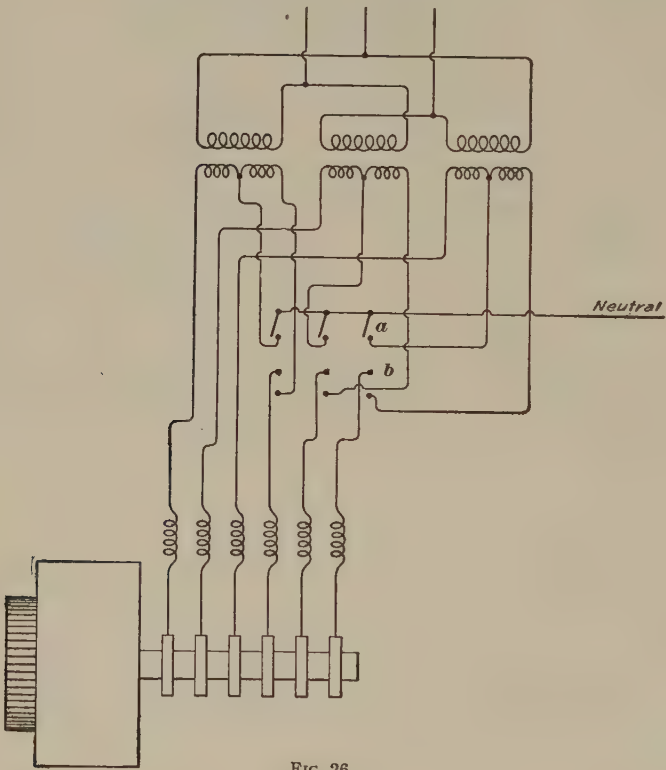


Fig. 26

of each secondary winding is brought out to a three-pole, single-throw switch *a* that connects the neutral points together during operation but is opened while starting. A three-pole double-throw switch *b* provides a means of supplying the converter with one-half normal secondary voltage for starting and full voltage for running.

73. Starting With Direct Current.—Fig. 27 shows the essential connections for starting a rotary converter with direct current from the load bus. During starting operations, the main positive switch *a* is open and the armature is supplied through the resistance. After the machine is synchronized, the main switch is closed and the starting switch is opened.

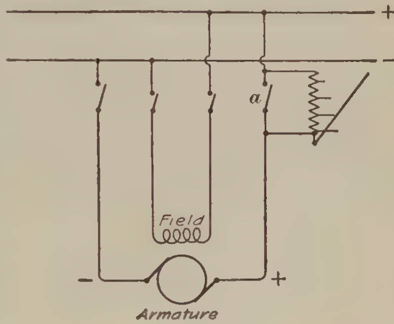


FIG. 27

The connections shown in Fig. 27 require a separate starting resistance for each machine. In order that one starting box may serve for a number of machines, a small starting bus *a*, Fig. 28, connected to one of the main busses through the starting resistance, is used. Each synchronous converter can be connected to the starting bus by means of a starting switch *b*. Two starting resistances can be arranged in conjunction with a double-throw switch *c* so that either can be used for starting any machine in the substation. The starting resistance is usually proportioned to carry the starting current for only one

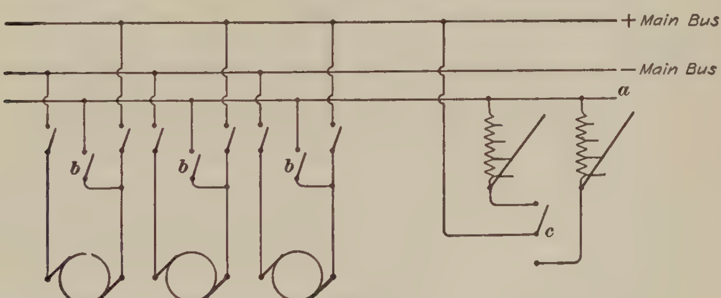


FIG. 28

machine, and the attempt to start two or more machines simultaneously would probably burn out the resistance. Starting switches such as shown in Figs. 27 and 28 should be left open except when needed for starting a machine.

SYNCHRONIZING CIRCUITS FOR ROTARY CONVERTERS

74. Circuit With Secondary Switches.—In order that synchronous converters that are started with direct current may be properly synchronized to their sources of supply, it is necessary to install suitable synchronizing circuits and devices. These synchronizing devices and connections do not differ in principle from those used in generating stations. There are, however, some special adaptations that require brief descriptions.

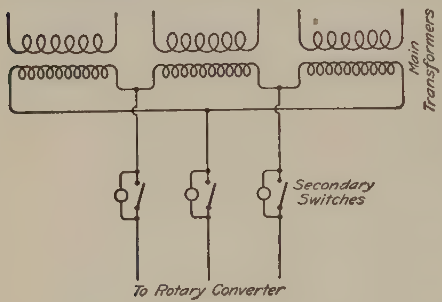


Fig. 29

Converters synchronized to the secondaries of their transformers with secondary switches have the simplest form of synchronizing circuit, as no step-down pressure transformers are necessary. If synchronizing lamps are used, they

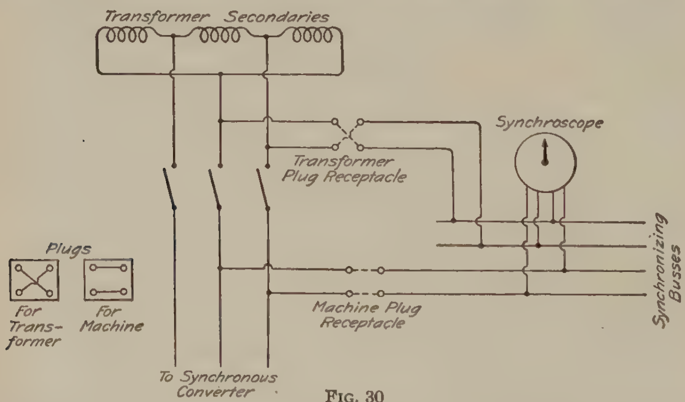


Fig. 30

are connected across the secondary switches as shown in Fig. 29, in which the circuit is arranged for synchronizing by dark lamps.

75. Synchroscope Connections.—When a synchronism indicator, or *synchroscope*, is used, it is desirable to have one instrument for use with all the units in the substation. This is accomplished by an arrangement shown diagrammatically in Fig. 30, which is a form of connection suitable for use with ungrounded synchronizing circuits. The simpler arrangement using grounded circuits cannot always be used in this case, as it would result in grounding the phase leads of the transformer secondaries and of the rotary converters.

When the units are synchronized with the transformer primary circuit, the high voltage on the supply side of the synchro-

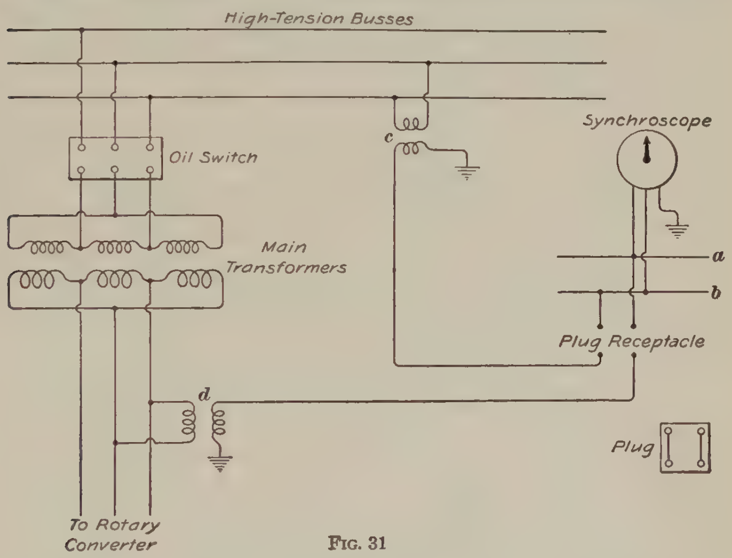


FIG. 31

nizing switch makes necessary the use of step-down potential transformers. There is usually no objection to grounding one terminal of the potential transformer secondary coil to permit simplifying the synchronizing circuit. In Fig. 31, one synchronizing bus *a* is connected to the armature and the other *b* is connected to the field winding of the synchronism indicator. The potential transformer *c* connected to the high-tension busses has a ratio of transformation such as to give a secondary voltage suitable for the instrument. A potential transformer *d*

connected to the secondary leads of the step-down transformers supplying the rotary converter has such a ratio as to deliver the same voltage as the potential transformer on the high-tension bus. Each potential transformer has one terminal of its secondary winding grounded. The connections of the synchronism indicator are then as shown.

76. Alternating-Current Voltmeter Connections. In order that a rotary converter when synchronized to the supply may not immediately take up too much load, either direct or inverted, it is necessary that the voltages on both sides of the synchronizing switch be equal. In order that the voltages can be observed, an alternating-current voltmeter is connected to a multiple-point voltmeter switch wired to each source of synchronizing current.

AUTOMATIC SYNCHRONOUS-CONVERTER SUBSTATIONS

77. Definition.—A synchronous-converter substation is considered to be automatic when the various functions of starting, stopping, and regulating the converter are performed without the presence of an attendant in the station with the machine. Such of the control apparatus as are not automatic are manipulated by an operator located in a distant controlling station, which may be another substation.

78. Purpose.—Automatic synchronous-converter substations are useful where central-station service in a given district is to be improved, yet the load density in that district is not great enough to warrant the expense of maintaining an attended substation. With the automatic substation, the expense of heating the building is saved and the labor expense is reduced to the cost of daily inspection.

79. Starting.—A synchronous converter in an automatic substation is most conveniently started as an alternating-current motor, reduced voltage during acceleration being obtained by means of a starter in the controlling station.

The field break-up switch is automatic; just before the converter reaches synchronous speed, a special governor on its shaft closes the control circuit of contactors that operate to connect the field circuit to the direct-current bus-bars so as to give a field of the correct polarity. The voltage of the converter is then raised by means of an induction regulator in the controlling station. At the moment that the voltage across the brushes exceeds that across the bus-bars, the converter is automatically connected to the direct-current system by the operation of a differential contact-making voltmeter. This voltmeter closes the circuit through the closing coils of the circuit-breakers whenever the direct-current voltage of the converter exceeds the bus voltage by a small percentage.

80. Regulation.—Voltmeters connected through pressure wires to various points in the portion of the network supplied by the automatic substation inform the operator at the controlling station of the voltage conditions on the system, and the load on the converter in the automatic station is changed accordingly. Changes in load are effected by manipulating the induction regulator in the controlling station. The amount of load on the converter at any time is indicated by alternating-current ammeters, an indicating wattmeter, and a power-factor meter in the controlling station. Complete overload, underload, and reverse-current protection is provided.

81. Stopping.—The rotary converter is stopped by disconnecting the alternating-current supply at the controlling station. This permits the machine to rotate as a direct-current motor taking a reversed current sufficient in amount to operate reverse-current relays. The operation of the reverse-current relays opens the main circuit-breakers and disconnects the converter from the direct-current bus-bars. As the machine slows down, the field contactors open, breaking up the field winding, and everything is automatically placed in readiness for a new start.

The commutating-pole type of synchronous converter cannot be used in an automatic substation unless a special automatic mechanism is provided for raising and lowering the brushes.

ALTERNATING-CURRENT SUBSTATIONS

FREQUENCY-CHANGER SUBSTATIONS

INDUCTION-MOTOR-DRIVEN FREQUENCY CHANGERS

82. Motor-generators used as frequency changers are of two kinds: those consisting of alternating-current generators driven by induction motors and those of which the generators are driven by synchronous motors.

The induction-motor-driven sets are undesirable if close regulation of frequency is required, and they cannot be used for inverse operation, that is, for frequency conversion except in one direction. One form of induction motor used for driving generators of frequency-changer sets is constructed with a wound rotor provided with slip rings on the shaft and with brushes and leads connecting to an external resistance. With an induction motor of this type, the speed of the machine can be regulated for synchronizing the generators and also for effecting control over the distribution of load between units. With motors having wound rotors, the resistances in the rotor circuits are considerable, and a suitable form of control is provided so that the speed of the motor can be regulated from the switchboard.

The design of a substation containing frequency changers driven by induction motors is of the simplest kind; the induction-motor installation being such as has already been described. The design of the generator installation should be similar to that of a steam-generating plant with alternators of the same size and capacity.

SYNCHRONOUS-MOTOR-DRIVEN FREQUENCY CHANGERS

83. Synchronous-motor-driven frequency changers are more complicated than those driven by induction motors, and attention to details of connections is necessary if more than one

unit is to be installed. The synchronous-motor installation should be along the lines already described; the high-tension busses, oil switches, step-down transformers, air-blast equipment, starting facilities, synchronizing circuits, exciting apparatus, and synchronous motors differ in no particular respect from a synchronous-motor installation for driving a direct-current generator, except that the speed of the unit must be common to the two frequencies. When the frequency of one end of the machine is double that of the other, as, for example, fifty and twenty-five cycles, there is a wider range of speeds for the machine designer to choose from. If the ratio between the frequencies is not a whole number there is usually but one speed practicable.

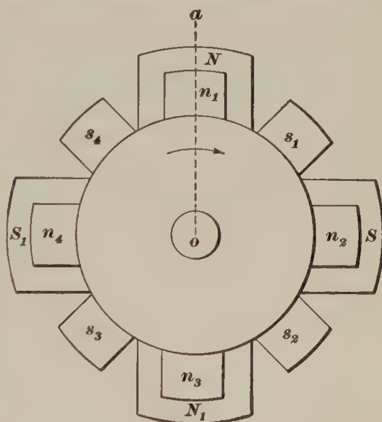


FIG. 32

84. The alternating-current generator of a frequency-changer set is connected to the same kind of switchgear as would be used in a steam plant using similar generators, and, although there is no speed control of incoming units, it is necessary to install synchronizing circuits and, in some cases, a synchroscope.

In Fig. 32 is shown, roughly, the rotor of a synchronous motor-generator. The assembly consists of a four-pole field N, S, N_1, and S_1 and an eight-pole field n_1, s_1, etc. mounted rigidly on the same shaft. If the four-pole end is to be considered as a motor, it is convenient to assume that the supply is obtained from a four-pole, revolving-field alternator and is transmitted through a line having no reactance. Then, when the motor runs without load and at synchronous speed, the center line through one of its north poles N or N_1 will be parallel to a line $o\,a$ imagined to be rotating about the motor-generator shaft in unison with the center line of one of the north poles of the alternator. Each north pole of the four-pole end of

the motor-generator lines up with a north pole of the eight-pole end; therefore, the generator end, in this case the eight-pole end, will be in phase with a similar unloaded unit already in operation from the same supply.

An examination of Fig. 32 shows that two north poles of the eight-pole end line up with north poles of the four-pole end, and two north poles of the eight-pole end line up with south poles of the four-pole end. Therefore, when the eight-pole end, operating as a motor, reaches synchronism, the four-pole end, now acting as a generator, may be in phase or 180 electrical degrees out of phase with the generator end of a similar unit driven from the same source of supply.

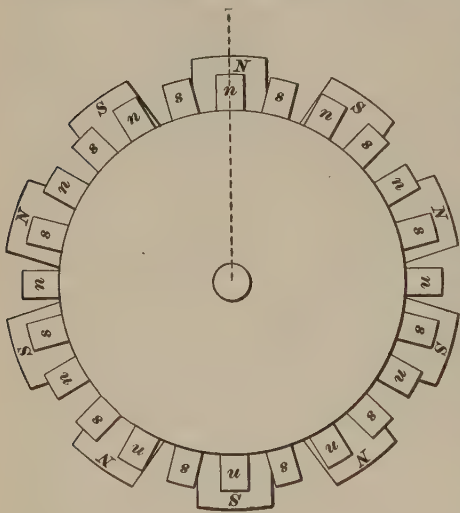


FIG. 33

85. From the preceding, the following general statements are derived:

If the number of poles of one end of a synchronous motor-generator is double that of the other, the synchronizing instrument can be dispensed with, and voltmeter indications can be relied on for paralleling the generator end with a similar unit. When the low-frequency end of such a machine is operating as a motor, no synchronizing equipment of any kind will be needed. If the high-frequency end is used as a motor, an indicating voltmeter connected between a generator terminal of one machine and the corresponding generator terminal of the other will indicate nearly zero voltage if the two generators are in phase or about double voltage if they are 180 electrical degrees out of phase. The generators must be brought into phase before connecting them in parallel.

86. If, however, the frequency change is not in the ratio of 1 to 2, or 2 to 1, the possible phase relations between generators are more complicated. In a 25-cycle–60-cycle motor-generator the frequency of one end is 2.4 times that of the other, and for every cycle, or 360 electrical degrees, of the 25-cycle end, the 60-cycle end will have 2.4 cycles, or $2.4 \times 360 = 864$ electrical degrees. The usual arrangement of the rotor of a 25-cycle–60-cycle synchronous motor-generator is shown in Fig. 33, ten poles on the 25-cycle end and twenty-four poles on the 60-cycle end. The diagram shows that only one north pole of one end is in line with a north pole of the other end. Therefore, if one motor-generator is in operation, motorized on the 25-cycle end and without load, and another similar set is started, there will be five different relative positions in electrical phase which the generators may bear to each other, only one of which would be correct for paralleling. This phase relation will remain constant because both motors are operating synchronously and, therefore, there is no difference in frequency of the generators. In order to change the phase relation it is necessary to advance or retard the motor in electric phase, which is accomplished in the manner described in *Operation of Electrical Machinery*, Part 2.

TRANSFORMER SUBSTATIONS

TRANSFORMER SUBSTATIONS FOR RAILWAYS

87. For railway systems employing only alternating-current motors on the cars, the substations, where used, contain protective devices, transformers, control equipment, and indicating instruments. No moving machinery is employed, and, aside from inspection and resetting of circuit-opening devices, the substation requires little attention. Sometimes, the substation is so located that an employe engaged on other work may, when necessary, be called by an automatic signal to attend to the circuit-breakers.

In Fig. 34 is shown a set of connections for a transformer substation of a single-phase railway system. Time-limit relays are

provided to open the circuits in case of a serious short circuit of considerable duration, but for slight overloads or temporary short circuits, the relays do not allow the substation to be cut out. Differential relays are installed to open the circuit in case the trolley line, owing to some disorder, causes the transformer secondary coil to act as a primary.

Transformer substations are generally equipped with voltmeters, or potential indicators, and ammeters for use in the

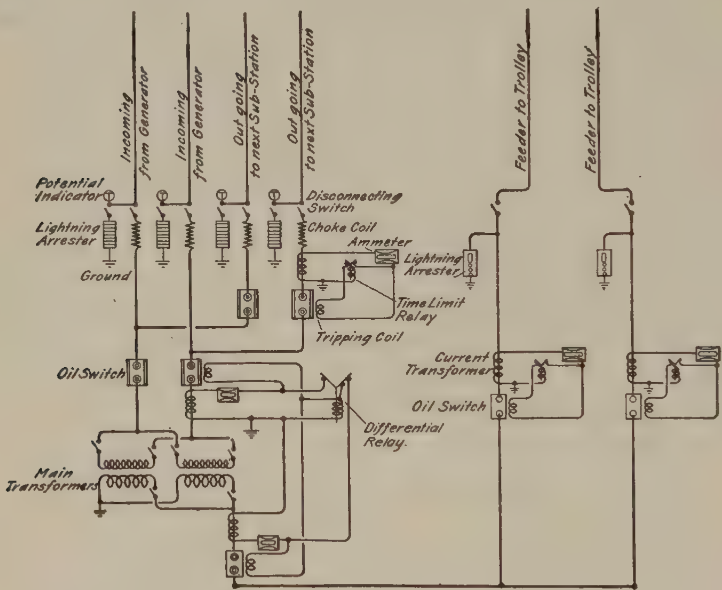


FIG. 34

location of faults. Both the high- and the low-tension feeders are equipped with lightning arresters. The main transformers must be of the self-cooling oil type.

TRANSFORMER SUBSTATIONS FOR LIGHT AND POWER

88. For central-station work, transformer substations are used where the frequency of the current in the distributing system is the same as that of the current in the transmission

lines, but the voltages are different. Such a substation, in its simplest form, may contain only one transformer with switches but without other switchgear except, perhaps, lightning arresters. Voltage regulation in such cases can be obtained by means of voltage regulators at the generating station. In other cases, the number of feeders is large enough to require equipment with potential regulators and the presence of an operator during the periods of heavy load. In the larger substations, when the service is important, two incoming high-tension lines with a tie-switch between them are provided so that the entire substation load can be carried on either line. As in railway substations, switches must be provided on each side of each transformer so that any transformer can be completely isolated from the system. When there are more than three or four feeders outgoing from a substation, the low-tension busses are preferably installed in duplicate, necessitating the use of double-throw switches. In the usual four-wire, three-phase, feeder system each phase is independent, and single-pole feeder switches are therefore employed, as it is both unnecessary and undesirable to open all phases when trouble occurs on only one.

89. Outdoor Substations.—In large hydroelectric developments in which energy is transmitted over long distances at very high voltages, large outdoor substations are frequently employed. In these outdoor transformer substations, the high-tension apparatus is installed outdoors and the low-tension apparatus in a switch house. Transformers, oil switches, and electrolytic (aluminum-cell) lightning arresters rest on concrete foundations in the open. High-tension leads and bus-bars are supported by steel structures on concrete. These structures, as well as the transformer tanks, are thoroughly connected to a ground bus.

The transformers of the larger stations are generally of the oil- and water-cooled type; in smaller stations, the self-cooling oil type can be used. The high-tension oil switches are generally of the remotely controlled type, solenoid-operated. Automatic control is secured by the use of inverse time-limit relays.

Disconnecting switches of the horn-gap type are placed so as to be operative from the ground, and, in most cases, are provided with safety catches to prevent accidental opening. Hoods over the switches prevent the formation of sleet on the safety catches.

The transformers are frequently mounted on wheel bases, so that, if necessary, a transformer can readily be placed on a truck and transferred.

The chief advantages of outdoor transformers over those of the indoor type are lower first cost, ease of making extensions, lower fire hazard, and simplicity of layout. It is estimated that the cost of a small outdoor substation is from 25 per cent. to 50 per cent. below the cost of an indoor substation of the same capacity. This saving decreases, however, as the size of the substation increases. Some of the precautions to be observed in operating outdoor substations is to use only low-temperature electrolyte in the aluminum lightning arresters, to guard against freezing of the water in water-cooled transformers, and to enclose the apparatus so that neither persons nor animals can be injured by coming in contact with high-tension circuits.

OPERATION OF ELECTRICAL MACHINERY

(PART 1)

Serial 1648A | Edition 1

INTRODUCTION

PRELIMINARY INVESTIGATION

1. Immediately on taking charge of any electrical machinery, the operator should acquaint himself thoroughly with the nature of the apparatus that will be under his care, including the scheme of connections of each unit, the connections of all of the auxiliaries and operating devices, all of the mechanical details, the normal and safe overload capacities of the equipment, all regular and any special limitations as to the performance of the equipment, and all sources of danger of physical injury. Unless entirely familiar with his plant, the operator may be unable to proceed properly in trying to locate defects in the equipment; he may damage the apparatus by overloading it, or may expose himself to serious personal danger or even to loss of life.

SAFE OPERATING TEMPERATURES

2. It is important that the operator bear in mind and apply in practice certain temperature limitations that experience has indicated to be proper. Temperature limits, often considerably lower than the temperatures at which immediate damage occurs, may, if long continued, cause insulating materials

to deteriorate gradually, leading to eventual breakdown, or may so change the magnetic properties of an iron core as to cause it always afterwards to heat seriously in normal operation.

3. Insulation made up of cotton tape and linseed oil, which is quite generally used for insulating the windings of air-blast-cooled transformers, should not be operated at a temperature higher than about 90° C., or 194° F. It is much better not to exceed a temperature of 80° C., or 176° F., as this lower temperature causes much less rapid deterioration. At a little above 90° C. is the critical temperature at which the insulation begins to carbonize, a process that gradually converts insulation into a conductor, thus reducing its insulating and dielectric properties, a condition favorable to breakdown.

Cotton insulation painted with black asphaltum insulating paint, such as is commonly used for insulating armature windings of low-tension machines, is able to stand about the same temperatures, but the process of deterioration is generally somewhat slower.

4. Magnetic cores of transformers and generator armatures are made of a special grade of steel with a high permeability, in order to reduce the hysteresis losses. If, however, the steel is subjected to too high a temperature, even for only an hour or two, its magnetic properties may be so impaired that it will always afterwards have larger hysteresis losses and, consequently, will heat unduly, even under light loads. This effect becomes accumulative in some degree; the greater losses produce higher temperatures, which still further damage the iron. Experience has shown that for the grades of steel now in use for magnetic cores, the temperature limits given above for cotton insulation are about correct.

5. Knife-blade switches so constructed as to depend partly on elasticity, or spring effect, of the copper parts for tightness of electric contact should never be heated to the point at which the temper of the copper is reduced. Operation at a lower temperature may be carried on without injury. As commercial copper differs so much in quality, it is impossible to

name the critical temperature at which the temper is drawn, but, for many kinds of switches in use, it is about 75° C., or 167° F.

6. Bare copper used for conductors into which the joints are secured by more reliable means than the spring effect, as, for instance, by bolts, may be much hotter without injury, and a temperature of 212° to 230° F. would not be dangerous. However, it is important to observe whether or not the high temperature is causing expansion of the copper, which may

TABLE I

SAFE TEMPERATURE OF TRANSFORMER OIL

Per Cent. of Full Load	Excess Temperature of Coils Over Oil Degrees C.	Safe Temperature of Oil, Coils at 90° C. Degrees C.
40	2	88
60	4	86
80	7	83
100	10	80
120	15	75
140	20	70
160	26	64
180	33	57
200	40	50

result in a mechanical strain at any of the joints, a condition that might cause poor contact and excessive heating at the joint.

7. Bearings of machines should not be operated at temperatures that would cause the Babbitt to soften, but if the bearings are kept properly oiled there is not much danger of this trouble. Babbitt bearings may be safely run at 160° F., or 71° C., and brass bearings still hotter. If the hand can be held on the outside of a bearing without great discomfort, the temperature is usually safe. It should be borne in mind that the internal temperature of a bearing is much hotter than the

external, and the sensation experienced by placing the hand on the outside of the bearing should be only a guide to enable the operator to judge as to the internal condition.

8. Oil used for cooling transformers is partly carbonized by long, continued overheating. The result is the formation of a thick, muddy deposit, which settles in the oil passages and, in time, so obstructs the circulation of oil as to cause overheating of the transformers. The temperature of the oil may be regarded as a fairly good means of obtaining the approximate internal temperature of the coils. The values given in Table I may be safely used for this purpose. The temperature of the oil is taken at the surface and near the transformer casing.

OPERATION OF ELECTRIC MOTORS

DIRECT-CURRENT MOTORS

PRELIMINARY INSPECTION

9. A direct-current motor, when set up and connected, should, before being started, be given a critical inspection, with a view to determining its mechanical and electrical condition. The armature must rotate freely in its bearings, all the electric contacts must be good, the machine anchored securely in its position, the connections correct, and the brushes well seated and under proper tension on the commutator.

SHUNT MOTORS

10. Starting.—Direct-current motors larger than about $\frac{1}{8}$ horsepower are, in almost all cases, started at a suitably reduced voltage, in order to avoid too great a current, which might injure the windings. The most common method of obtaining the reduced pressure for starting is by means of a starting box, or rheostat, inserted in the armature circuit. The procedure in starting a motor so equipped is as follows:

1. See that the starting resistance is all in circuit, that is, the arm of the rheostat is in the starting position.

2. Close the main armature switch (line switch) or circuit-breaker.

3. Slowly move the arm of the starting rheostat from its initial position, point by point, until it has reached the limit of travel and all the resistance is cut out. If, instead of a simple starting box, the starting resistance is also used to control the speed, stop cutting out resistance when the desired speed has been reached.

4. If the starting box, or speed controller, has an automatic low-voltage release, see that the rheostat arm is securely held in place by the retaining magnet.

5. Examine the motor to see if the bearings are getting sufficient oil and if the commutation is practically sparkless.

If the motor fails to start on the first step, the rheostat arm should be moved promptly to the second step and, if necessary, to the third step. If the motor fails to start on the third step, the line switch should be opened at once, the rheostat arm allowed to go to the off-position, and an inspection begun for faulty connections, overload, etc.

The foregoing instructions do not, of course, apply to motors equipped with automatic starters.

11. Time Required for Acceleration.—The time required for speeding up the armature of a direct-current motor is dependent on the size and weight of the rotating mass. An armature of a 1-horsepower motor should ordinarily not require more than about 15 seconds for bringing it from rest to full speed. If, however, there is mechanically connected to the armature, either by direct coupling or by belt, a rotating body having a large amount of weight at a considerable distance from the center of rotation, the time of acceleration should be considerably increased. Failure to observe this precaution may result either in blowing the fuse in circuit with the motor or, possibly, in damaging the motor armature. Twenty-five seconds is ordinarily sufficient for speeding up a motor of from 25 to 75 horsepower if there is no heavy connected load, and

motors up to 500 horsepower may be accelerated in from 60 to 70 seconds.

If there is an ammeter in the motor circuit, its indications will be the best possible guide as to the proper rate of cutting out starting resistance. If the starting rheostat has a considerable number of contact points, as, for instance, ten or fifteen, the rheostat arm may be moved just fast enough to prevent the current from becoming greater than about 80 per cent. of the initial rush of starting current. If the starting rheostat has only a relatively small number of contact points, as, for instance, from three to six, the arm or switch blade should be held at each point until the current, as indicated by the ammeter, has practically stopped decreasing in value, at which time another section of resistance should be cut out.

When ammeters are installed, they should be frequently observed, as their indications enable the operator to know at once whether or not the motor is taking too large a current. As a rule, such instruments are not provided in connection with small motors and only infrequently with moderate-size ones.

12. Running.—During the operation of the motor, routine inspections should be made to see that no mechanical or electrical trouble is developing.

The field circuit of a shunt motor or the shunt-field circuit of a compound-wound motor should never be opened, even for an instant, while current is being supplied to the armature, as the result may be such a dangerous increase in speed as to cause the rotating parts to be seriously damaged. In some such cases, the centrifugal force is sufficient to cause the commutator to fly to pieces and the conductors of the armature winding to fly out of their slots; this constitutes one of the dangers of physical injury incident to improper operation of shunt- and compound-wound motors. It is customary to protect motors against such a result by inserting current interrupting, or cut-out, devices in the motor-armature circuit. When the current in the field circuit is interrupted, the magnetic flux cut by the armature conductors is very much reduced and the counter electromotive force of the motor is also reduced, thus

permitting a larger current in the armature. If the current-interrupting devices, either fuses or circuit-breakers, operate quickly enough, damage is avoided, but in many cases the acceleration is so rapid that the time element of fuse or circuit-breaker allows a dangerous speed to be reached before the circuit is opened.

Speed control of both compound and shunt motors is sometimes effected by the use of a variable resistance in the armature circuit. The operator should examine this resistance often enough to satisfy himself that it is not overheating, and that there are developing, in resistance conductors, contact arm, or contact buttons, no faults that could result in opening the circuit.

Before shutting down the motor, the operator should assure himself that the bearings are not heating unduly. Overheated Babbitt may *seize*, or, as it is frequently expressed, *freeze*, when cooled, and thus render it impossible to turn the armature when cold. This remark applies with equal force to all rotating machinery, and special mention of procedure in handling bearing troubles is given later.

13. Stopping.—The usual procedure in shutting down a motor is to simply open the main switch or the circuit-breaker. When this is done, all automatic devices return to their normal starting positions, so that if the switch is again closed no harm will result. After the motor is at rest, the operator should, however, carefully inspect the automatic devices, in order to see that they have operated properly. The arm of a starting box provided with automatic release should never be forced back to stop a motor; that type of rheostat is not designed for interrupting the current. Some types of combined starting and speed-control rheostats are made to open the motor circuit; but even with these, it is advisable to open the line switch, if the motor is to remain idle for some time.

With most drum-type controllers used with machine-tool equipment, a quick stop can be made by moving the handle quickly to the first running notch, holding it there for a moment, and then moving it to the off-position. An emergency stop

can be made by moving the handle to the first running notch, letting it rest there momentarily, and then moving it to the first reversing notch. This last method should never be used except in emergency, and in using it the handle should never be moved beyond the first reversing notch.

14. Reversing.—The direction of rotation of the motor armature can be reversed by reversing the direction of the current in either the armature or the field circuit, but not in both. If the motor is provided with a reversing switch for this purpose, it is used in the armature circuit. If no reversing switch is provided, the current supply should be cut off and the armature allowed to come to rest. Either the field or the armature terminals may then be reversed according to convenience.

COMPOUND MOTORS

15. Polarity Test.—Before starting a compound-wound motor for the first time, see that the series and shunt fields agree in direction, unless intended to act differentially. The test for polarity may be made by opening the series field circuit of the motor and sending current through the shunt circuit, as in Fig. 1 (*a*), observing by means of a pocket compass or permanent bar magnet the polarities of the pole pieces, then disconnecting the shunt circuit, sending current through the series circuit in the direction that it will have in operation, and repeating the observation for polarity. Under the latter condition, the field flux will generally be rather weak, even when the current is equal to the full ampere rating of the motor, and it is important that the device used for determining the polarity be fairly sensitive. In testing the series circuit, it is generally necessary to limit the current by a suitable resistance, such as a bank of incandescent lamps, connected as shown in (*b*).

16. Operation.—The methods of procedure followed in the operation of compound-wound motors are similar in some respects to those used for shunt motors.

A compound-wound motor can be started and stopped in the same manner as a shunt motor. Owing to the influence of the

series current, the accumulative compound motor has a strong starting torque. Its speed regulation is not as good as that of a shunt motor and, in some cases where good speed regulation is of importance, a special provision is made for shunting the series field after the armature is up to speed. Care must be taken that the special shunt circuit has good contacts and low resistance, or else a considerable current will still pass through the series field. The operator should frequently examine all the contacts in this shunt to see that they are clean and to prevent the development of a resistance that is high as compared with that of the series-winding.

The direction of rotation of the armature should be reversed by changing the direction of current in the armature rather than in the fields, since there are two field windings, each of which would require reversal, thus making the change more difficult and increasing the liability of making wrong connections.

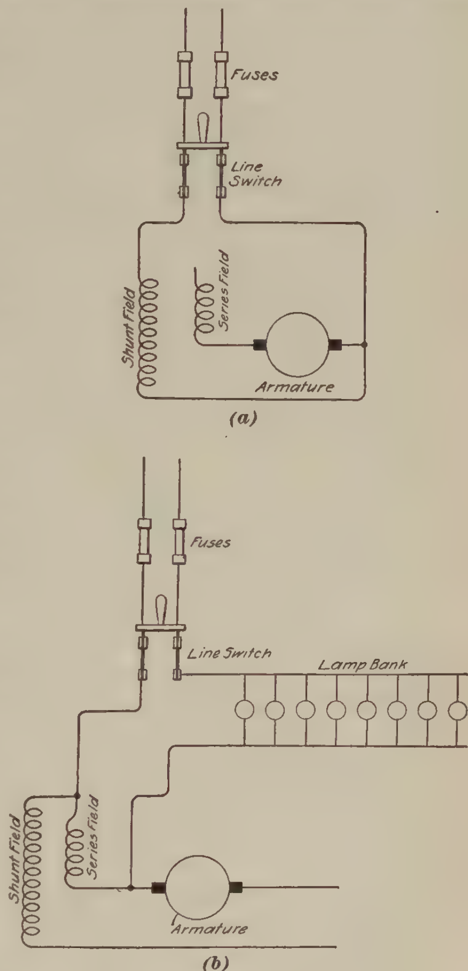


FIG. 1

SERIES MOTORS

17. Series-wound motors are generally used for heavy duty where speed regulation is of comparatively little importance. Like shunt motors, they are started with a resistance to limit the flow of current. In many cases, as in electric cars, this starting device is so designed as to perform, also, the duties of a controller for starting, stopping, and reversing the motor and for regulating speed.

A characteristic of series motors is that when running unloaded their speed becomes excessive. This is a dangerous condition and should be avoided by mechanically connecting such motors so that the load can never be entirely removed, as by coupling or gearing to the driven machine.

ALTERNATING-CURRENT MOTORS

STARTING

18. Procedure.—Alternating-current motors, both induction and synchronous, require for starting and acceleration a current several times that required for full-load operation. Alternating-current motors, unless of very small capacity, cannot be started at full potential on account of the voltage drop that would be caused by the heavy rush of current, and also on account of the possibility of fuses being blown or windings injured by the large currents. The reduced voltage necessary for starting is derived from a starting compensator, or autostarter, or from sectional-winding connections in the transformers supplying the motor, or by the use of a starting rheostat similar to those used with direct-current motors. A starting compensator constitutes a main-supply switch as well as a starting device, but an additional main-supply switch is generally installed.

The procedure in starting an alternating-current motor, either induction or synchronous, by the starting compensator is as follows:

With the lever of the starting compensator in the off, or open, position, close the main supply switch and all other switches in series between the compensator and the supply, thereby bringing the supply pressure up to the terminals of the starting compensator switch.

Throw the lever of the compensator into the starting position and leave it there while the rotor is accelerating in speed.

When the rotor is up to speed, or nearly so, throw the lever arm of the compensator quickly over into the running position. In some cases, a latch is arranged to catch and hold the lever in the off-position if the movement from starting to running position is made too slowly.

In starting a motor with reduced potential derived from sectional taps from the transformer supplying the machine, a double-throw switch similar to the switch of the compensator can be used, or, if preferred, two separate switches so interlocked, mechanically or electrically, that only one switch can be closed at a time. The procedure is the same as that for starting by the compensator, but the danger of running temporarily on reduced voltage is not so great provided the motor is running light. With reduced voltage, an induction motor will run slower than normal, but, if unloaded, will not heat seriously, and the transformer will not be damaged.

19. Time Required for Acceleration.—Except in the case of a large motor, that is, one having rotating masses at a considerable distance from the center, the time required for the rotor to reach full speed will usually be rather short, generally less than 1 minute. A 5-horsepower motor with a rotor from 12 to 16 inches in diameter should be up to full speed in from 10 to 15 seconds; a 50-horsepower motor with a rotor having a diameter from 18 to 25 inches should be at full speed in 20 to 25 seconds; and, in the larger sizes, a 500-horsepower motor with a rotor 5 or 6 feet in diameter ordinarily requires about 40 to 45 seconds to reach full speed.

The operator will very quickly learn to recognize full speed by the sound produced by the rotating body. If there is a connected load, so that the motor is pulling against a consider-

able mechanical drag, the operator should be very careful to observe the rate of change in tone, and, if possible, change the supply voltage from starting to running pressure slightly before the motor has reached a constant speed. If the starting pressure is applied too long, the motor will be running at reduced potential and with excessive slip, and the starter may be overheated. The autotransformers in such a starter are designed to be in service only a few seconds at a time, usually not to exceed a minute; the copper and iron parts are therefore much smaller and the cooling arrangements are less complete than in a device intended for continuous service.

20. Causes of Poor Acceleration.—When an alternating-current motor appears to speed up too slowly, the cause is generally either too much load or too low a starting voltage. Low starting voltage may be due to taking the starting circuit from the wrong taps in the compensator windings, or to a poor electric contact either in the compensator switch or in the external circuit.

21. Field Excitation of Synchronous Motors.—When the procedure just given has been followed in starting and accelerating an induction motor, the operation is complete. A synchronous motor, however, must have its field winding excited with direct current before it can be put under load. When the motor has reached full speed, the field switch and all other switches in the circuit between the direct-current supply and the field windings should be closed.

The correct excitation of a synchronous motor is a matter of considerable importance. If overexcited, the motor will operate with a leading current; if underexcited, the current will be lagging. Either condition results in sending through the armature a larger current than is necessary, causing avoidable heating of the armature winding. Under ordinary conditions, therefore, the field current should be adjusted to such a value that the motor operates at unity power factor.

22. For the correct determination of the proper amount of field current, either an ammeter or a power-factor indicator is required. In connection with large units, the power-factor

indicator is generally installed, but with smaller installations an ammeter is commonly used on account of its lesser cost.

In using the power-factor indicator, the rheostat in the motor-field circuit should be so adjusted that the pointer on the instrument will remain, as nearly as possible, at the 100 per cent. mark.

An alternating-current ammeter in the armature circuit can be used for the proper regulation of the power factor, although it does not indicate the power factor directly. At unity power factor, all the current is in phase with the voltage, and for a given amount of energy and a given voltage the current is then the least. Therefore, if the operator adjusts the field rheostat of the motor so that either strengthening or weakening the field will increase the amount of current, as indicated by the ammeter, the condition of unity power factor will be obtained.

The power factor of a synchronous motor running with a load that is small compared with its capacity cannot be maintained at unity except by continual attention. Such close attention is, however, unnecessary, as, although the wattless component of the current in a synchronous motor running on light load is a very large percentage of the total, the actual energy being supplied is small; consequently, the total current may not be large enough to be objectionable.

23. Sometimes, owing to conditions beyond the control of the operator, unity power factor cannot be obtained in the operation of a synchronous motor. As a synchronous motor can be overloaded in current by improper field adjustment, even though delivering less than the rated mechanical load, the current input should then be carefully watched. If the motor is provided with an ammeter, instead of a power-factor indicator, the load condition can be observed directly, and, as the normal full-load current rating of the machine is usually marked on the name plate, it is possible to determine whether or not the motor is overloaded in current and by what amount. If no ammeter is provided, the current load cannot be found without the use of a voltmeter, a wattmeter, and a power-factor indicator.

EXAMPLE.—During the operation of a 6,600-volt, 250-kilowatt, single-phase, synchronous motor, the instrument indications are as follows: Voltmeter, 6,000; power-factor indicator, .80; wattmeter, 200 kilowatts. The normal current rating of the motor is 38 amperes. How much, if any, overload is the motor taking?

SOLUTION.—As shown in *Alternating Currents*, watts = volts $\times$ amperes $\times$ power factor, or amperes $= \frac{\text{watts}}{\text{volts} \times \text{power factor}}$. Then, the current taken by the motor is $\frac{200 \times 1{,}000}{6{,}000 \times .80} = 41.7$ amp., nearly. The overload is $41.7 - 38 = 3.7$ amp., or $3.7 \div 38 = 9.7$ per cent. Ans.

It is worthy of note that in this example two factors, low voltage and low power factor, combine to produce the overload. With normal voltage, the low power factor would, in this case, have caused the motor to take only its full rated current; with unity power factor and the voltage at 6,000, the motor would have taken only 33.3 amperes.

In applying the foregoing method of calculation to a three-phase motor, it is essential to know whether the voltmeter is connected between neutral and phase wire, indicating star pressure, or between two phase wires, indicating delta pressure. If delta pressure is indicated, the expression for current is

$$\text{amperes} = \frac{\text{watts}}{1.732 \times \text{volts} \times \text{power factor}}$$

24. Synchronous motors are sometimes operated with overexcited fields, in order to compensate for the low power factor produced on a distribution line and at the generating station by induction motors. If the induction-motor load on the distribution line is large in comparison with the synchronous-motor load, complete compensation for the lagging current due to the induction motors may not be possible. The compensation must not be carried beyond the safe carrying capacities of the armature conductors of the synchronous motors. All the precautions against overloading must be taken, and the operator should, if possible, take observations to determine the power factor on the supply line at a point between the generator and the motors.

25. Effect of Interrupted Circuit.—If the alternating-current supply to a synchronous motor is interrupted, even for

a second or two, the speed of the rotor will be reduced by the retardation of the mechanical load, and the electromotive force generated by the motor will be lower in frequency. To restore the full voltage of the supply circuit at such a time will probably cause an abnormal current and a resulting mechanical shock, the severity of which will be in proportion to the difference between the instantaneous pressures of line and motor at the time the circuit is completed. This difference is greatest when the motor and line electromotive forces are out of phase by 180 electrical degrees. The interrupted supply to a synchronous motor should not be restored except through the proper starting procedure.

Induction motors, being non-synchronous, are not required to operate under such exacting conditions as synchronous motors, although if the current supply is interrupted long enough to permit any considerable reduction in speed, the motor switch should be opened. When the cause of the interruption has been remedied, the motor should be started in the usual way. In some cases, the starters are provided with no-voltage releases that automatically return the contacts to the off-position whenever the current is cut off; in other cases, the starters must be opened by hand.

26. Observation of Slip.—The speed of an induction motor decreases slightly as the load increases. As soon as possible after taking charge of an induction motor, the operator should determine the slip that occurs at various loads, and, if operating large motors, should occasionally take observations to see if the slip is greater than it should be. Excessive slip may be caused by poor contacts in the primary or secondary circuits. Loose bars in squirrel-cage rotors are a form of poor contact in secondaries.

OPERATION OF DIRECT-CURRENT GENERATORS

PRELIMINARY INSPECTION

27. Generating machinery should not be started for operation without first being subjected to a careful inspection. The condition of the brushes and of all electric contacts that are liable to any considerable change should be determined. Any foreign articles, such as tools, rags, waste, etc., found in or about the machine should be removed. If possible, the operation of the switches in the circuit should be tested.

The condition of the armature switches of a direct-current generator is a matter of considerable importance, as inattention to the contacts may result in serious overheating. If conditions permit, each switch should be tested by being closed and opened several times to see that it works freely. The armature circuit must not be closed to live busses unless the generator is up to speed and has the same voltage and polarity as that of the busses; otherwise, the busses will be virtually short-circuited by the low resistance of the armature circuit.

SHUNT GENERATORS

28. Starting.—A direct-current generator should be brought up to normal speed gradually. After the armature has begun to rotate, the surface of the commutator should be cleaned by using a cloth or piece of waste slightly moistened with engine or dynamo oil, the commutator passing first under the oily rag and then immediately under a dry cloth to remove most of the oil, leaving the surface very slightly moistened with oil and free from accumulations of dirt. During the latter part of the acceleration, the operator should observe the polarity and potential of the generator.

29. Tests for Polarity.—If a direct-current generator is to be paralleled to any other source of potential, it is, of course, necessary that the polarities of both be alike. It is also necessary for the proper indication of measuring instruments that the direction of current is correct.

If a direct-current voltmeter properly connected across the open leads of the generator armature shows a reversed indication, the polarity is incorrect. The voltmeter indication can be checked by allowing the generator to reach full speed and voltage and then switching in series between each armature lead and the live bus to which the lead is intended for connection a sufficient number of incandescent lamps in series to require for full brilliancy the normal voltage of the machine. If the polarity is correct, the lamps will not burn; if it is reversed, they will burn at approximately full brilliancy. The connections for reversed polarity are shown in Fig. 2. For a 110-volt system and 110-volt lamps, the distribution of potential will be as indicated in (*a*) if the polarity of the generator is reversed, assuming no resistance in any of the conductors except the filaments of the incandescent lamps.

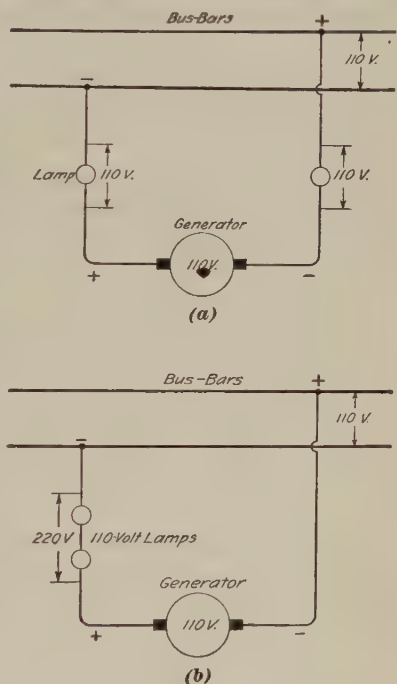


FIG. 2

The test just described can be varied to suit the facilities at hand. For example, the generator may be closed on one side, or terminal, to the bus on which it is to operate, and all the lamps connected between the other armature lead and its bus connection, as shown in (*b*). If the polarity of the machine

is incorrect, as indicated, the lamps will burn at about full brilliancy; if correct, the lamps will not burn.

Instead of the lamps connected as in (*b*), a portable voltmeter capable of taking twice the normal voltage of the generator can be used. If the polarity is correct, the voltmeter indication will be very low—zero, when the pressures on the machine and bus are equal. If the polarity is incorrect, the voltmeter will show the sum of the machine and bus voltages.

30. Correction of Reversed Polarity.—If, by observation and test, it has been determined that the polarity is reversed, the armature should be brought to rest and the polarity corrected by the safest and most easily applied method available. If a bus to which the generator can be connected is alive and of correct polarity, all the brushes of one polarity (either positive or negative) are raised from the commutator and the main armature switches of the generator are then closed. This will send current through the field windings in such a direction as to produce fields of the proper polarity. After a few seconds, the armature switches are opened, care being taken to open the circuit very slowly by gradually increasing the distance between the knife blade and the contact clip.

When the circuit is broken in this manner, a long, flaming, hissing arc will occur at the switch, but the operator should feel no concern, as the arc is perfectly normal under this condition. It is quite important that the switch is opened slowly, as a quick break would cause to be established in the highly inductive field circuit an electromotive force that might be great enough to damage the insulation. The brushes can be separated from the commutator by putting paper under them.

If inconvenient to raise all of the brushes of one polarity from the commutator, a machine lead can be disconnected between the armature and the tap for the shunt field. This is really the safer method of opening the armature circuit, because, in the first method, if one brush is overlooked, there will be a short circuit. It should be remembered that the object of either method is to establish a current in the field circuit, but not in the armature windings.

Further directions for the correction of reversed polarity of a direct-current generator are given in *Operation of Electrical Machinery*, Part 2, under the heading Care and Maintenance of Electric Machinery.

31. Adjustment of Voltage.—When the polarity is correct, an observation should be taken to determine the voltage of the generator. If the machine is to be connected to busses not already alive, the voltage may be brought to normal by adjustment of the field rheostat and the armature may then be connected to the busses by means of the armature switches. The voltage is adjusted by varying the current in the field windings; increasing the field current, increases the voltage, and vice versa. If a series rheostat is used, the field current is increased by cutting rheostat resistance out of circuit and is decreased by the reverse process. With a shunt rheostat, the field current is increased by increasing the rheostat resistance, and vice versa.

32. Correct Voltage for Paralleling.—If the generator is to be paralleled to some other source of current, as a storage battery or other shunt-wound generators, the voltage must be correct for paralleling. The correct theoretical voltage of the incoming machine depends on a number of factors; but, practically, it may properly be about 2 or $2\frac{1}{2}$ per cent. higher than that of the busses to which the machine is to be connected. This will cause the generator to take a little load as soon as connected, which is not objectionable, if not too great, and is generally desirable for engine-driven units, as it is not advisable to risk motorizing the generator. If the paralleling is done at equal pressures, some variable condition may cause a reversal of current through the generator, thus tending to drive it as a motor.

If the load is steady and the speed regulation of the driving power of the generators is very good, the voltage differences just given can be reduced, and, if conditions are sufficiently reliable, paralleling can be performed at equal voltages. With voltages equal, the generator is brought into service entirely without load, a practice that can be recommended when the

conditions are favorable or when a slight motorization of the generator is not objectionable, as, for instance, when the generator is being driven by a synchronous or a direct-current motor.

When putting a generator into service for the first time or when the proper voltage difference for paralleling is not known, it may be regulated to 2 or 2½ per cent. greater than that on the busses to which the machine is to be connected. After paralleling, the rheostat may be adjusted until the load is as small as can be held steadily without danger of reversal. Then if the armature switches are opened and readings of both the bus and the generator pressures taken, the operator will have obtained, once for all, the most desirable relation between generator and bus voltages for safe and proper paralleling of these particular generators. It must be remembered that not all machines designed for the same voltage require precisely the same relation, as they differ greatly in armature characteristics.

33. Adjustment of Load.—After the generator voltage is correctly adjusted and the main armature switches are closed, the operator should at once observe, by the ammeter, the amount of load taken, in order to see that no unusual or dangerous condition exists. The generator may then be put under load by increasing its field strength. If the addition and loading of the generator renders necessary the transfer of load from other similar machines, the reduction of load on the others is obtained by weakening their fields by means of the rheostats. The transfer of load from a storage battery is obtained by reducing its potential by means of the end-cell switches, booster generators, or other means provided for the purpose. The added generator may then be continued in operation, its load being regulated by the field rheostat, increasing the field strength to increase the load on the generator and weakening the field to reduce the load.

Though the operation of shunt machines in parallel is a stable condition, unsafe load conditions can be developed by transferring to one or more machines a larger load than they can carry safely, and this may be done merely by reducing the

load on some other unit. This emphasizes the importance of observing the load on each generator every time that a change of adjustment is made in the load on any one. In addition, routine observations of load conditions should be made at frequent intervals, the frequency of inspection depending somewhat on the character of the service.

34. Regulation.—As the load on the station increases, that on each generator is also increased and the station voltage is reduced, thus requiring an increase in the field strength of each machine. If the generators are so designed as to be all alike as to armature characteristics, and if under the lighter load condition all were loaded in the same proportion to capacity, then under the heavier load condition this proportion will continue. If, however, the armature characteristics of the different generators in parallel are unlike, those generators having the largest internal armature drop will take less than their share of the increase of load and those having the lesser internal drop will take more than their share of the increase. If the generators were all alike as to armature characteristics, but not loaded alike in proportion to their capacities, the machines carrying the largest percentage of full load would take less than their proportional part of the increase. This last-named feature tends toward safety of load distribution, and therefore is not liable to develop dangerous load conditions. With unlike characteristics, however, lack of proper attention may result in too much load being thrown on some of the machines.

The reverse conditions as to regulation are, of course, true, but no dangerous load conditions are liable to develop as a result of reduction of load except when the latter gets so light as to interfere with the proper operation of the driving machinery. Some types of steam engines do not work reliably when lightly loaded, and care should be taken not to allow the load to get down to the point where racing or unsatisfactory speed regulation results. Such conditions cause variations in the voltage and impair the service. It is better practice to reduce the number of units in operation until those remaining

in service are fairly well loaded, thus improving both the regulation and the economy.

35. Effect of Excessive Overload.—If a load equal to several times normal rating is thrown on a shunt generator, its voltage and current will be reduced practically to zero. Under such a condition, although the armature may continue to rotate at full speed, the machine will be without electromotive force until the excessive load is removed. Generally, severe sparking of the brushes occurs at first when a shunt machine is heavily loaded or short-circuited; but the result is usually not destructive, as the drop in pressure causes an immediate reduction of field current, this resulting in a further lessening of the electromotive force, the effect being cumulative until the pressure and current are both zero.

COMPOUND GENERATORS

36. Paralleling.—A compound generator is started, accelerated, observed for polarity, and regulated for voltage in the manner described for shunt machines. But the parallel operation of compound-wound generators provided with the same terminal connections as shunt machines is unstable. The proper closing of equalizer switches is a matter of extreme importance in connection with paralleling compound-wound, direct-current generators, and the operator should never perform the paralleling operation without first checking the conditions of the equalizer circuit and seeing that the equalizer switch is closed. Failure to do so may result in motorizing one of the generators, reversing its polarity, or, in some cases, so severely overloading the windings of one of the units as to cause serious damage.

Two forms of practice are followed in adjusting the generator pressure before paralleling: The pressure of the incoming machine is adjusted before the equalizer switch is closed. The series-field windings of the running and incoming machines are placed in parallel by means of the equalizer switches and then the pressure is adjusted. Though the first method is,

perhaps, the more common, the latter is the better practice, as the compounding effect of its share of the load is produced before the generator is connected, thus permitting a more exact control over the amount of load that will be taken when the paralleling is completed. In the operation of railway generators, on which the load fluctuations are large, one method is practically as good as the other.

37. Regulation.—A change in voltage of a compound generator can be made by means of the field rheostat as with a shunt machine; but the compounding effect of the series-winding, under the influence of load changes, performs, automatically, much of the regulation that would require manipulation of the rheostat of a shunt machine. If the compounding is properly adjusted, the series field will correctly regulate the pressure for all changes in load within limits, and the compounding effect can be changed to suit the required conditions; that is, adjustment can be made to give a constant voltage at the station busses, or, if preferred, a little overcompounding can be produced to compensate for a drop in pressure in the distribution system and thus to maintain a constant pressure at some designated feeder terminal.

The method of changing the amount of compounding is to change the amount of resistance in the German-silver shunt connected in parallel with the series-field winding. If additional compounding is desired, more current is diverted through the series-winding by increasing the resistance of the shunt. If less compounding effect is required, the resistance of the shunt is reduced.

It should not be assumed that once a generator is started and put into service its voltage will require no further observation or adjustment; because, as the windings heat up under the influence of the load current, their resistance increases, which increases the armature drop and also decreases the shunt-field current. For this reason, the operator's attention will be required to see that the proper pressure is maintained.

38. Compound Generators With Storage Batteries. On account of the increase of electromotive force as the load

increases, a compound-wound generator is not suitable for operation in parallel with storage batteries, because the pressure of a storage battery, like that of a shunt generator, decreases as the load increases. As soon as a compound generator, paralleled with a storage battery, delivers any current to the battery, the effect is to increase the voltage of the machine, which then sends more current through the battery, the effect becoming accumulative within limits. If the series-field winding is shunted by a heavy copper bar and the series-field circuit opened, the machine is converted into a shunt generator, which operates well with a storage battery.

SERIES GENERATORS

39. Series-wound generators are used principally for supplying constant direct current for series-arc-lamp circuits. No new installations are being made, and the treatment herein covers only the general principles applicable to all the various types of series generators still in use.

Care must be taken that a series generator is correctly connected to the circuit; a reversal of the polarity of the circuit will cause the arcs to burn upside down.

Usually, one circuit is connected in series with each generator, but two or more circuits can be connected in series with one another and the combination connected to one machine, provided that proper attention is given to polarities and that the total voltage required by all lamps does not exceed the voltage capacity of the generator.

If one generator is underloaded and another in the same station is overloaded, two lamp circuits can be connected in series with the two machines, in order to distribute the load more evenly. One machine is then generally made to generate a constant voltage by making its automatic regulator inoperative, and the other machine, with its regulator, takes care of the load changes. Two forms of connection for this method of distributing a load are shown in Fig. 3, in which arrows are drawn to show current direction. The system shown in (*b*) has the

advantage over (*a*) of placing a lower voltage to ground on the generators in case a ground occurs on a lamp circuit.

40. In general, the lamp circuits should, when possible, be connected to the generators before the machines are started.

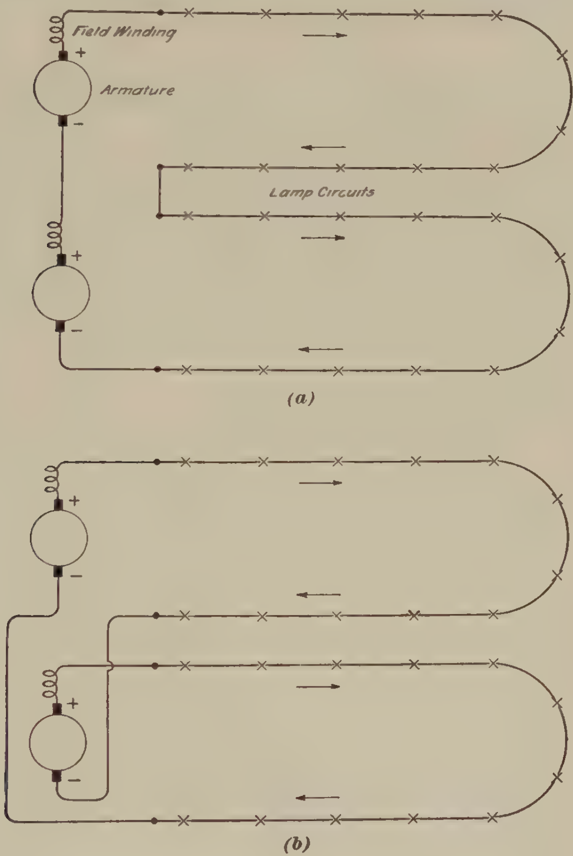


FIG. 3

A lamp circuit should never be disconnected, unless the voltage of the machine to which the circuit is connected is first reduced to practically zero by short-circuiting the field, the armature, or the machine as a whole.

Sparkless commutation on an arc machine is not to be expected, but for any given type of generator there is a normal spark that the operator should learn by observation, and the cause of any abnormal sparking should be promptly located. Some of the possible causes are faulty brush setting, poor current regulation, or a break in the armature circuit.

FIELD CIRCUITS OF DIRECT-CURRENT GENERATORS

41. Self-Excited Generators With Field Switches. In all that has been said so far about the operation of both shunt- and compound-wound generators, the operating practice described is such as should be followed with machines connected without any field switches or other convenient means of opening the field circuit. Direct-current generators operating self-excited should, in general, be connected without switches in the shunt-field circuit.

When field switches are provided, it is, of course, necessary that they be closed before the unit is started, or the machine will not generate. It is even a matter of more importance that while a generator, either shunt or compound, is operating in parallel with any other source of current, its field circuit be kept closed. If the field circuit should be opened, either by mistake or otherwise, the machine having no excitation would stop generating, and the armature, still connected to the other source of current, would be a short circuit of low resistance. If not promptly disconnected from the bus-bars, either by the operator or by automatic protective devices, the other units may be overloaded and damaged. If sufficient capacity in compound generators or in storage batteries is in parallel with the unit with the open-field circuit, its armature will be burned out if not disconnected at once.

42. Separately Excited Generators.—In some installations, it is desirable to operate generators excited either from the busses or from a special exciting set. In such cases, it is necessary that the precautions, before mentioned, are observed

with reference to any interruption of the field circuit. When generators operating in parallel are neither self-excited nor excited with current from the load busses, all should be excited from the same exciter set, or some other means should be taken to make impossible the interruption of the field-current supply to a part and not all of the units.

EDISON THREE-WIRE SYSTEM

43. All the foregoing instructions on the operation of direct-current generators applies to the Edison three-wire as well as to the two-wire system. Only the system of connections shown in Fig. 4 requires special mention; because, though the operation of the individual generators is not greatly affected, the regulation of the station voltage is more complicated than in the two-wire system.

44. Owing to the importance of maintaining nearly constant voltage at customer's premises, general central-station practice is to regulate the bus-voltages so as to give standard conditions at feeding centers in the distribution system. Observations of voltage at these points are obtained by means of voltmeters connected through pressure wires to the feeder terminals, and the voltages on the two sides of the system at a feeding center are kept equal. It is therefore necessary to regulate together all the generators on each side of the system and to observe carefully the result on the relative pressures of the two sides.

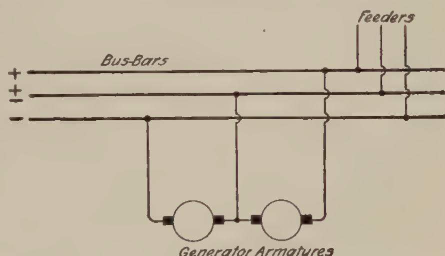


FIG. 4

If the load is perfectly balanced throughout the distributing system, the bus pressure will be balanced also, but this is a condition that seldom exists, and usually the pressures on the two sides of a three-wire system are unlike at the station. If

it is observed that the pressure of one side is becoming too low or too high, correction should be made in the same manner as on a two-wire system; but when regulating pressure on one side, attention must also be given to the other side. High or low pressure on one side may be the result of either one of two possible conditions: Load conditions existing on one side and not on the other may make one side high or low; or the total pressure between the positive and negative sides may be unchanged and the generators on one side may be delivering a higher or lower voltage than those on the other, although the connected load may be the same on each side. The second condition amounts practically to a displacement of the neutral and is to be corrected by regulating the generators on both sides, reducing pressure on the high-voltage side and raising it on the other.

TIRRILL REGULATORS WITH DIRECT-CURRENT GENERATORS

45. The Tirrill regulator for use with direct-current generators is described in *Direct-Current Generators*. The procedure in the operation of the form for generators of small or medium size is as follows:

Before connecting the regulator, mark the position of the generator field rheostat arm at which the generator pressure is reduced about 30 per cent. below normal when the regulator is not in operation.

With the generator in operation at normal voltage and either with or without load, and with the main and relay contacts of the regulator closed, close the switches connecting the main control magnets to the direct-current supply (if any such switches are provided), and close, also, the switches connecting the relay contacts to the field rheostat. Turn the rheostat arm gradually to the marked position. The regulator will begin operation as soon as the voltage has been reduced sufficiently to operate the relay, and afterwards will keep the pressure at the value for which the instrument is adjusted.

If one or more generators are in operation with Tirrill regulators, another may be connected in parallel as follows: Equalize

the voltage of the incoming machine to that of the units in operation, close the switches connecting the regulator relays to the field rheostat of the incoming generator and close all other regulator switches pertaining to this unit. Close the main armature switches. Equalize the load by means of the equalizing rheostat in the generator that has the most sensitive regulation.

46. In order to take out of service one of several generators in parallel, reduce its load, open its armature switches, and then open the regulator switches corresponding to this machine.

To take the regulator out of service, assuming one generator is in operation, turn the arm of the generator field rheostat toward the strong field position. When the relays stop vibrating, open the switch that connects them to the field rheostat. Pressure regulation may then be carried on by means of the generator field rheostat.

In order to avoid unequal burning of the main and relay contacts of the regulator, the current through them should be reversed about every 6 hours of operation. This is done by means of the small reversing switches on the bottom of the regulator panel. If the contacts burn unevenly or develop tips, they should be evened with a strip of very fine emery paper or cloth. As the contacts are made of precious metal, no more material than necessary should be removed.

47. Large direct-current generators to be regulated with Tirrill regulators must be excited by a special exciting generator, a particular form of regulator being used. The relays shunt the field rheostat of the exciter generator instead of the main generator rheostat. The regulator has a potential coil supplied from the main generator, load busses, or back feed from the feeding center, as preferred. If a switch is installed in circuit with this potential coil, it must be closed before starting the regulator. The procedure is as follows: With the generator in service at normal voltage and the regulator main and relay contacts closed, close the switches connecting the potential coil to the busses or generator or back feed from

distributing center, as the case may be, and close the switches that connect the relays to the exciter field rheostat. Gradually, turn the exciter field rheostat arm to the position that would, under normal conditions, cause the exciter to generate a pressure about 35 per cent. below normal. The regulator will start operating as soon as the generator voltage drops enough to start the relays. Set the main generator field rheostat in a position for a strong field, if this setting can be obtained without disturbing the operation of the regulator.

ROUTINE CARE AND INSPECTION

48. During operation, direct-current generators should be frequently inspected to see that they are working under proper conditions. Bearings should be examined at least every ½ hour to see that a sufficient supply of oil is passing through them to avoid overheating. The commutator should be kept clean, and care should be taken to see that brushes do not get hot.

A hot brush on the commutator indicates a poor contact and relatively high resistance. Frequently, the fault is on another brush, which, unable to carry its proper proportion of the load, overloads the brush in parallel with it, though the latter has good contact and relatively low resistance. Not only the brushes that are overheating should be inspected, but the condition of the others, also, should be observed. If only one brush on a stud is heating, the trouble is probably confined to that one.

49. The operator should, as far as possible, observe the temperatures of the generators, at least to the extent of feeling the field coils and placing his hand in the air discharge from the armature. He should always be on the alert for any odor of burning insulation or for any unusual noise. Any of these conditions requires his immediate and continuous attention until the cause and its seriousness are determined and the fault remedied. A generator that is apparently burning out or smoking from overload should be relieved and shut down as

quickly as possible. Whether it shall be disconnected before another is started to take its load, or continued in operation with the risk of further damage until relieved, depends on the character of the service and the extent to which the trouble has already progressed. These matters are for the operator to decide and a specific rule of general application cannot be given. A generator that breaks down while operating in parallel with other sources of current may short-circuit the latter and cause serious damage; therefore, it should be separated from other units as quickly as possible.

OPERATION OF ALTERNATING-CURRENT GENERATORS

PRELIMINARY INSPECTION

50. Alternating-current generators should receive the same general preliminary inspection as direct-current generators. The operator should make certain that each machine is free from foreign objects, such as tools. The brushes should be inspected to see that they are firm and secure in place and make good contact with the collector rings. If possible without connecting the machine to a live circuit, the switches should be tested by operation. The operator should assure himself that all connections have been properly made and that all connectors are firmly secured.

The exciter set that is to supply the field current should also be subjected to inspection. It is a mistake to assume that because the exciter set is small and somewhat in the nature of a piece of auxiliary apparatus, it can be neglected without serious risk. Without it, or some other source of exciting current, the alternating-current generator is useless, and experience has shown that in alternating-current installations the exciter generator is often the weakest part. The operation of the exciter is carried on in accordance with the methods already described for direct-current generators.

OPERATION OF SINGLE ALTERNATOR

51. Starting.—If the exciter set is driven separately from the alternator, it should be up to speed and voltage before the alternating-current generator is started. This is merely for convenience, so that when the alternator has been started, it can be excited without delay. In installations where the exciter is belted from or is directly connected to the generator shaft, this convenience is not possible. If the alternator is to go into service alone and is to pick up circuits not already alive, it is brought to normal speed and excited with a weak field; that is, with the rheostat resistance in circuit in both alternator and exciter fields, causing the generator to deliver a low voltage at normal frequency. This is done so that when the generator is connected to the dead circuits, which may have a considerable connected load, the rush of current, which will exist for an instant, will be small. All the switches between the generator and the busses to which it is to be connected are then closed, the circuit completed by means of an oil switch, if there is one in the circuit, and the alternator voltage is then brought up to standard by means of the alternator and exciter-field rheostats.

52. Regulation.—As the field current of the alternator is quite large compared with the field current of the exciter, the greatest economy in the use of field current will be obtained by operating with as little resistance as practicable in the alternator field rheostat and performing most of the regulation by means of the exciter rheostat. Hence, this method should be used unless it results in operating the exciter at a pressure too low for good regulation. To obtain good voltage regulation, the exciter must be operated with a magnetic density so great that a relatively small change in field current will not produce a large change in magnetism and consequently in voltage. This density is not at the saturation point, but is considerably above the steep part of the magnetism curve. The operator will be able to determine whether or not he is working with too low an exciter pressure by observing the direct-current

voltmeter (or if none is provided, a lamp) connected across the terminals of the exciter generator. If there is any difficulty in keeping a steady voltage with slight variations in exciter load, which can be produced by means of the field rheostat of the alternator, the pressure of the excitation system should be raised until stable operation is obtained, the field rheostat of the alternating-current generator being adjusted as required to keep the alternating current at the proper voltage.

Voltage regulation of the alternator is carried on by means of the generator and exciter-field rheostats, and for machines operating alone, that is, not in parallel with any other units, the regulation is a very simple matter.

SERIES OPERATION

53. Alternating-current generators cannot be operated in series unless they are so coupled, mechanically, that they are in phase and cannot vary their phase relations. This may be, and is sometimes, done for special purposes by having their rotating parts mounted on the same shaft and the windings so alined that the armature electromotive forces generated will be in phase with each other. If alternators are driven separately, the condition will be unstable, the electromotive forces being in the same direction at one time and opposed at another, the final condition tending to establish exact opposition. With equal and opposite machine voltages, there would be no voltage across the external circuit.

PARALLEL OPERATION

SYNCHRONIZING

54. Checking Synchronous Connections.—The operator must know whether lamps used for synchronizing are connected to indicate the in-step condition when they are either at their greatest brilliancy or entirely dark. If the connections are covered, or otherwise difficult to trace, the circuit can be checked

by disconnecting the leads of one alternator at points between armature a and the synchronizing circuit, as at b, Fig. 5, and then closing the main alternator switches c as for paralleling the alternators. With the connected machine d in operation, both sides of the synchronizing circuit will be energized from the same source if the synchronizing switch e is closed; then the indications of the lamps will be those correct for synchronizing. The main switches of the disconnected alternator armature a should then be opened and the machine reconnected at points b. This method applies to voltmeters and synchroscopes also.

55. Synchronizing With Lamps.—Some skill is required to determine the proper conditions for paralleling when lamp indications are used. The difference in frequency between the running and incoming units must not be too great, else the division of load, after the machines are together, will be unsatisfactory; if the difference is too small, it becomes difficult to determine when the alternators are in phase. The difference in frequency will be clearly indicated by the "beat" of the lamps, and the operator must choose some speed with which he can best work; preferably, the beats should not be slower than once in 10 seconds nor faster than once in three. If the synchronizing is done with dark lamps, the paralleling (main switch) connection must be made at the middle of the interval between the disappearance of the last glow and the time the same amount of glow would reappear. The right instant for paralleling can be determined by watching the beat for some time while it is steady, counting at a moderate and even rate from the instant of disappearance to reappearance of the glow, and then dividing the count by two. If the counting is well done and the speed conditions are constant, the paralleling or synchronizing of the alternators will be well done.

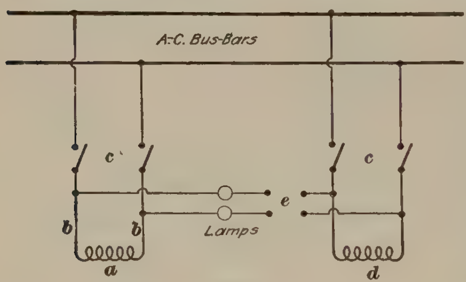


FIG. 5

If the pressure of the incoming alternator is not the same as that of the running units, cross-currents will flow between them; therefore, it is important to equalize their pressures by field adjustment before tying them together electrically. If, when using synchronizing lamps with a slow beat, the lamps do not go entirely out, the pressures are not properly equalized.

56. If synchronizing is to be done with bright lamps, the paralleling connection is to be completed at the instant that the lamps are at their maximum brilliancy. This is more easily determined than is the middle of the dark period, but considerable care is necessary. If the operator is too far from the lamp, he may not be able to see well enough to determine accurately the instant of maximum brilliancy. If he is too near, the light will be somewhat dazzling; then the pupil of his eye will, in a short time, fail to enlarge and close with the variation in brilliancy of the lamp, with the result that he will be inaccurate in deciding the instant when the maximum brilliancy occurs. It is not possible to state just how far away the synchronizing lamp should be, as the distance will vary with the individual, but it must be experimentally determined by each operator for himself. If the position of the lamp is fixed too near to or too far from the switch, its position can be changed to suit the individual by putting it on the end of an extension cord.

57. Since the lamps, by their beat, indicate only the difference in frequency between the running and incoming machines, they do not show whether the incoming unit is running faster or slower than the one already in operation. For this reason, the indications of the lamps should be observed, if possible, during the speeding up of the unit and continuously after that until the correct speed is obtained. If, after the incoming machine is up to speed, the beat should become too fast, the cause may be either high or low speed. Whether the incoming alternator is too fast or too slow can be determined by varying its speed and observing whether the frequency of the beat is increased or decreased.

58. Synchronizing With Voltmeter or Synchroscope. When using a voltmeter for synchronizing, it is necessary to

know whether the in-phase condition is indicated by the maximum or the zero reading of the instrument. The beat should be rather slow and the swing of the needle should be observed several times before the switch is closed. If the zero or the maximum indication is not obtained, it is an evidence that the alternating voltages are not equal.

The synchronizer, or synchroscope, gives an indication not only of the time of the in-phase condition and of the difference in frequency, but also shows whether the incoming alternator is running too fast or too slow. If correctly connected, the in-phase condition is indicated when the indicating hand is in a vertical position. Reasonable care should be taken not to connect the synchroscope in circuit until the difference in frequency between the incoming machine and the running units is small; when the difference is large, the armature of the instrument will not rotate, but will vibrate excessively.

59. Speed Control.—The method by which it is possible to make the difference in the frequencies of alternators slight depends on the kind of machinery used for driving them. Steam engines or waterwheels are usually equipped with some form of speed control. Some steam engines have governors that can be manipulated and by which the speed can be controlled; others, using shaft governors, are not subject to such control and the speed is partly controlled by the throttle.

60. Time Element in Switch Closing.—The armatures of the alternators are connected in parallel, in some cases, by closing a simple, hand-operated switch (either knife-blade or oil-immersed contact), and if this can be done quickly, that is, with a short time between the first movement of the hand and the completion of the connection, the operation is very simple. When remote-controlled oil switches are used, it is always necessary to make a proper allowance for the time required for the operation of the switch. The time needed should be known from previous observations.

61. Effects of Inaccurate Synchronizing.—Inaccurate synchronizing; that is, making the parallel connection when the potentials of the machines are too far out of phase with

each other, whether it results from unreliable indicating devices, wrong connections, failure to allow for time element of switches, or from any other cause, is a source of danger that may result seriously. The worst effect is produced when the electromotive forces are out of phase by 180 electric degrees, for then the cross-current will be maximum; but, even with a phase difference as low as 8 or 10 degrees, severe mechanical shock may result, the armature may be injured either mechanically or electrically, or the oil switch wrecked. The current and the extent of the damage resulting are dependent on the phase difference and also on the reactances of the armatures of the alternators. There are in use some alternators with armature reactances so great that two such machines may be connected together without serious result when completely out of phase; but they are not in common use, and the operator should always use the greatest possible care when connecting any alternators in parallel.

DISTRIBUTION OF LOAD

62. After alternators are tied together electrically and are operating in parallel, the distribution of load among them should be given immediate attention. The distribution of kilowatt load is dependent on the relative phase positions of their rotating parts. Alternators in parallel must run in perfect synchronism, yet it is possible for the engine, turbine, waterwheel, or other driving power, of one generator to force the rotating parts of the generator ahead in relative phase position by a few electrical degrees, as if it were making an effort to exceed the other in speed. Were it not for the synchronizing effort exerted tending to keep the machines in step, the leading unit would actually run with a slightly higher frequency than the others. The action is like that of a team of horses hitched to a load in such a way that, although they progress at the same rate, the more energetic horse does more than half the work; in fact, in extreme cases, it may do all the work, and even help to move its mate. The energetic horse is like the alternator that leads in phase. A horse that is dragged along by its mate corresponds to a motorized generator.

The kilowatt load on one of several alternators in parallel can be increased by causing it to pull ahead in phase; or, in other words, to tend to run faster than the other units (of course, it will not actually exceed the speed of the others); or, what amounts to the same thing, cause the other units to tend toward slower speed.

Prime movers with governors subject to control while running are better adapted to the control of load division between alternators than such machines as high-speed engines having shaft, or automatic, governors that are not subject to control during operation.

63. The value of the cross-current between two paralleled alternators is controlled by means of the field excitation, which, when improper, will cause to pass between the armatures a cross-current of an intensity depending on the difference in the field currents of the machines. The cross-current will exist, even though the prime movers are so adjusted that each alternator bears its proper share of the power (kilowatt) load. In the machine with the weaker excitation, the cross-current will be leading; in the other, it will be lagging. By simultaneously adjusting the field rheostats, the cross-current can be varied considerably without altering the voltage of the system. Under some conditions, an alternator can be made to take sufficient leading cross-current to cause it to operate at unity power factor, even though the load has a power factor less than 100 per cent.

In general, the excitation of alternators in parallel should be so regulated that they carry current loads in proportion to their ampere ratings. With proper field adjustment, the sum of the alternator ammeter readings will be a minimum, and the alternator power-factor meters, if provided, will all read the same.

In special cases, there may be reasons why the general rule should not be applied. For instance, one alternator may have been under heavy load for several hours and consequenty subjected to considerable heating, while another may have just been put into service. Again, as a result of age or service,

the insulation of one machine may be damaged so much that it cannot safely withstand the same heating that would be safe for a similar machine in good condition.

TIRRILL REGULATORS WITH ALTERNATORS

SETTING THE REGULATOR

64. The voltage regulation of alternators is obtained by changing the field currents. The principles governing this method of regulating an alternator operating alone apply to parallel operation also; in addition, it is important that the excitation of all alternators in parallel be given attention each time that the voltage is regulated, in order to avoid troublesome cross-currents.

One of the most commonly used automatic devices for the voltage regulation of alternators is the Tirrill regulator. Usually, each installation of such a device is subject to such conditions as to make some special procedure advisable; however, there are in connection with the operation of Tirrill regulators some principles that are general.

65. Assuming that the Tirrill regulator has been correctly connected and properly adjusted, but has not yet been put into service, start the exciter and alternator, and run the alternator without load. The alternator field rheostat should be turned until all its resistance is out of circuit; if less than 55 per cent. of the normal voltage of the exciter is then found necessary to produce the rated voltage of the alternator, the exciter voltage should be raised to at least 55 per cent. of its normal value, and the alternator voltage regulated by means of the alternator field rheostat. If the exciter field is so weak that the exciter voltage is less than 55 per cent. of normal, the machine will be under conditions of unstable regulation. When the exciter and alternator voltages are at the proper values, mark the position of the alternator field rheostat arm so that this position will always be known.

If two or more alternators for parallel operation are to be automatically regulated, they should be connected in parallel without load, and their field currents regulated by means of their field rheostats until they operate without cross-currents. At least one of the alternators may have all its rheostat resistance out of circuit. If, after regulating to eliminate cross-currents, it is found that less than 55 per cent. of the normal voltage rating of the exciter is required for producing the normal alternating voltage, adjust the exciter pressure to 55 per cent. normal and readjust the field rheostats of the alternators until the alternators deliver normal voltage and have no cross-current. When this adjustment is made, mark the positions of the alternator field rheostat arms for future reference.

66. The next step is to cut into the exciter field rheostat sufficient resistance to reduce the alternating-current voltage to about 65 per cent. of the normal full-load value, and to mark the position of the arm of the exciter rheostat. This should be done separately for each exciter set that is to be used with the Tirrill regulator.

Make the direct-current coil of the Tirrill regulator alive by closing the switch in circuit with it (if such a switch is installed), and make the alternating potential coil alive by closing to it the switch connected to the special potential transformer on the machine that is to be regulated. Close the switches that connect the relay contacts to the exciter rheostat. If the main contacts remain apart after the switches are closed, adjust the auxiliary contact arm in the alternating-current, control-magnet circuit until the contacts come together and the regulator begins working. The alternating-current voltage should then be adjusted to normal by moving the auxiliary contact arm, the final position of which should be marked or observed for reference when putting the regulator into service in the future.

ROUTINE OPERATION

67. The operations just described are not to be performed in routine operation, but are the steps to be taken in putting the regulator into service when it is first installed. After these

operations have once been performed, and the various rheostat-arm positions have been marked or observed so that the rheostats can be reset to those points, the procedure should be as given below; see *Voltage Regulation of Alternating-Current Circuits.*

Close the switch connecting the direct-current coil to the exciter busses that are to be used. In some installations, selector switches between different sets of busses are installed; in others, selector switches between different exciters. Close the switch connecting the alternating-current coil to the pressure leads from the alternator that is to be regulated. Adjust the auxiliary contact arm in the alternating-current, control-magnet circuit to the marked position. Set the alternator field rheostat arms to the marked positions, keeping the alternating-current voltage at normal by proper adjustment of the exciter-field rheostat. With the main contacts of the regulator apart, close the switch or switches (if more than one) connecting the relay contacts in shunt across the exciter field rheostat, and then slowly move the arm of the exciter rheostat to the marked position. The main contacts will come together and start the regulator.

If desirable, the alternating-current voltage can be changed by means of the auxiliary contact arm in the alternating-current, control-magnet circuit.

68. All the alternator fields supplied by the exciter working with the regulator will be subject to the operation of the regulator, and, if the installation is so made as to provide for using exciters in parallel in connection with the regulator, additional ones may be cut in by the following method: By means of its field rheostat, adjust the voltage of the incoming exciter to equal that on the exciter bus, close the main armature switches that connect the exciter to the bus, and immediately close the switch connecting the relay contacts in shunt with the field rheostat of this exciter and turn the exciter rheostat arm to the marked position.

A rheostat is generally necessary to equalize the load between the exciters; it should be adjusted for proper division of current and this adjustment should be made permanent.

To take one of two or more exciters operating in parallel and controlled by the same regulator out of service, first disconnect it from the exciter bus by means of its main switch and then open its rheostat-shunt switch. If it is desired to take the regulator out of service, turn the exciter field rheostat to cut-out resistance until the main and relay contacts stop vibrating and remain apart, then open the switch that connects the relay contacts in shunt across the exciter rheostat.

69. As machine characteristics vary somewhat, in connection with some installations, experience may indicate that the regulation of the exciters is unstable when the rheostat is adjusted as described. It should be remembered that the procedure given is for general cases, and that if conditions in some installations are special the procedure may be varied somewhat to advantage. The mistake should not be made, however, of trying to use the Tirrill regulator with the exciter-field flux near the saturation point; the exciter will work better if operated with a magnetic flux that will give rather unstable pressure when regulated by hand.

70. The Tirrill regulator should be kept in good adjustment, and a few minutes of each operating day should be spent in seeing that it is kept in good condition. The contacts should be kept smooth, pivots free, connections tight, and the adjusting nuts should not be allowed to work loose. The reversing switches in the feed to the main contacts and relay contacts should be reversed about every 6 hours of operation in order to prevent the contacts from burning away unequally. Excessive arcing at the relay contacts may be due either to insufficient condenser capacity in parallel with them or to an open circuit in the connections between condenser and contacts. In the first case, the remedy is to increase the number of condenser sections; in the second, to restore the connection.

In service, Tirrill regulators are subject to one form of trouble that seriously affects the pressure regulation, and this is the sticking or fusing together of its contacts, either main or relay, but more often the relay contacts. When the contacts fuse together, the generator pressure at once rises and it is necessary

to take the regulator out of service immediately. To do this, when the contacts are stuck together, open the switch that connects the relay contacts in shunt with the exciter rheostat and immediately strengthen the exciter field by cutting out resistance with its rheostat.

OPERATING TROUBLES OF ALTERNATORS

71. It is impossible to classify all the various forms of operating trouble that may occur in the use of alternators, and, also, to prescribe definite rules of procedure for each case. It is important, however, to mention, briefly, a few general rules that the operator should keep in mind.

As it is necessary that alternating-current generators be not connected in parallel without the proper synchronizing procedure, it is equally important that when, for any cause, an alternator has been disconnected from a live circuit, even for an instant, it be not reconnected except by synchronizing and standard paralleling methods. This rule does not always apply to alternators driven by synchronous motors, as will be explained in *Operation of Electrical Machinery*, Part 2.

Severe short circuits sometimes occur on distributing systems, and sometimes in the generating station on busses, or in the windings of broken-down generators. In such cases, the effect may be to reduce the pressure in the station or, automatically, to open oil switches. The short-circuited portion of the system should be isolated by means of oil switches as quickly as possible, in order to avoid the serious results that such an overload would produce on the generators.

The exciter system is a frequent source of operating trouble, and it is not uncommon to have the service of a large unit completely interrupted by some minor trouble with the exciter generator.

OPERATION OF ELECTRICAL MACHINERY

Serial 1648B (PART 2) Edition 1

OPERATION OF MOTOR-GENERATORS AND SYNCHRONOUS CONVERTERS

MOTOR-GENERATORS FOR CURRENT CONVERSION

INDUCTION-MOTOR-DRIVEN SETS

1. The operation of motor-generator sets converting alternating current into direct current, using either induction or synchronous motors, should be carried on in accordance with the methods for alternating-current motors and for direct-current generators. The simplest case is that of a direct-current generator driven by an induction motor, both of which are operated according to the instructions given in another Section.

SYNCHRONOUS-MOTOR-DRIVEN SETS

2. Starting From Alternating-Current Side.—Synchronous motors driving direct-current generators are generally excited from the output of the generators, and if direct current is not available until a machine is started, the procedure is as follows:

Start the synchronous motor by means of the starting compensator, leaving it unexcited until up to speed. Throw the

compensator handle to the running position and, as soon as the direct-current generator begins to pick up, close the field switch of the synchronous motor and all other switches necessary to complete the excitation circuit of the motor.

It is very important that no considerable amount of load be connected to the generator until the synchronous motor has been excited; therefore, if the motor-field circuit is connected to the generator leads, do not close the armature switches to the direct-current load busses until the motor is fully excited. If the field switch connects the exciting circuit to the load busses and if these are dead, disconnect the load, close the generator armature switches, and then the motor field switches, adjust the motor field rheostat, and then reconnect the load. If the busses are alive before the motor-generator is started, excite from them as soon as the motor is up to full synchronous speed and before closing the generator switches.

3. **Starting From Direct-Current Side.**—In some installations of this type, provision is made for starting the motor-generator by using the generator temporarily as a direct-current motor and synchronizing the motor to the alternating-current busses.

If the direct-current generator is compound wound, it should be provided with switches for reversing the series field for starting purposes. The procedure is as follows: Reverse the series fields, excite the generator by closing its field switch, if one is provided, adjust the generator field rheostat for strong field excitation, and close the starting circuit with all the resistance in circuit. If the generator is excited from its own leads, and has no field switch, the machine cannot be excited before closing the starting switch; but, as the starting current is limited by the resistance box, no harm will result. In this case, adjust the field rheostat for strong field excitation and close the starting circuit with all the resistance in circuit. When starting a set for the first time test the field poles with a piece of soft iron, and if the polarity is correct, gradually cut out resistance from the starting circuit until it is all cut out. If the machine is not then up to full speed, increase its speed to normal by gradually

weakening the field of the direct-current generator, now acting as a motor. Excite the synchronous motor by closing all the switches in its field circuit and synchronize the synchronous motor, now operating as a generator, using the methods for synchronizing an alternator.

When synchronized, open the armature switches of the direct-current end and reverse its series-field winding. If the shunt field is connected to the generator leads between the reversing switches and the main switches connecting to the bus-bars, opening the series-field reversing switches will also open the shunt-field circuit. In this case, care must be taken to open the first of these switches slowly, in order to avoid a quick opening of the shunt field and the possible puncturing of its insulation. The equalizer switch should then be closed, the pressure regulated by means of the generator rheostat, and the machine paralleled with the other direct-current units. In this case, because the speed relations of the generators are exactly maintained, the pressures of the incoming unit may be made equal to that of the busses instead of slightly higher. This is also proper if the generator is driven by an induction motor.

If the generator is shunt wound instead of compound wound, the procedure is the same as just described, except that no series-field reversing switches have to be operated, and no equalizer switch is to be closed.

4. Conversion of Direct to Alternating Current. The same motor-generator that is used for converting alternating to direct current can also be employed for changing direct to alternating. The methods of operation are practically the same as those for direct-current motors and alternating-current generators. For synchronizing, the speed of the alternator is regulated by means of the field rheostat of the direct-current motor, and after synchronizing, the distribution of load between alternators in parallel is controlled by the same means. By weakening the field of the direct-current motor, the alternator is given a tendency to advance in electric phase and to take a larger proportion of the energy load.

INDUCTION-MOTOR-DRIVEN FREQUENCY CHANGERS

5. The operation of the motor-generator frequency-changer sets is carried on in accordance with the methods for the operation of alternating-current motors and generators, but with some additions necessitated by special requirements. Since induction-motor-driven sets are not well adapted to inverse operation and do not run synchronously and therefore do not operate well together, frequency-changer sets are generally made with synchronous motors.

In the operation of induction-motor-driven sets, the motor is started in the usual manner, and the load is connected to the alternator after the motor is supplied with full running potential. Alternators driven by induction motors are not usually operated in parallel; but when such operation becomes desirable or necessary, the alternators are synchronized by varying the load on one of them, thus varying its speed by changing the slip of the induction motor. When the alternators are in phase, as indicated by the synchronizing devices, they are paralleled. There is no way of controlling the distribution of kilowatt load between two such units.

SYNCHRONOUS-MOTOR-DRIVEN FREQUENCY CHANGERS

FREQUENCY CHANGE IN SIMPLE RATIO

6. Ratio of One to Two.—The paralleling of synchronous-motor-driven frequency-changer sets is much more complicated than that of induction-motor-driven sets. The simplest case is that of sets for changing to double or half frequency.

If two such sets, unloaded, are started and brought up to synchronous speed by connecting their low-frequency ends, as motors, the high-frequency ends, on being excited, will generate electromotive forces that are in synchronism and in phase. But if the two units are unequally loaded before paralleling

them, the more heavily loaded unit will lag behind the other. Full load on a generator causes its low-frequency motor to lag about 25 electrical degrees behind the phase position it would have under no load, resulting in a lag of about 50 degrees in the generator electromotive force. The two generators of the synchronous-motor-generator sets may therefore run at the same frequency, but, before paralleling, be out of phase by an amount proportional to the difference in loads, the generator of a fully loaded unit being about 50 electrical degrees behind the generator of an incoming unit with no load. A phase difference of 50 degrees would be too great for paralleling steam-driven alternators; but with synchronous motors there is usually no way of controlling speed, and as the motors and generators will immediately equalize their loads as soon as connected together, the generators may be paralleled if their voltages are equalized. When they are connected in parallel, heavy cross-current and synchronizing current will exist for a few seconds, after which, if the units are similar, they will divide the load properly.

7. Ratio of Two to One.—If the same two units are started from the high-frequency ends, the electromotive forces of the low-frequency generators at no load may be in phase, or 180 electrical degrees out of phase.

If the unloaded generators are 180 degrees out of phase, the simplest means of correcting the phase difference is to reverse the direction of current in the field winding of one generator, which reverses the instantaneous polarity of the generator electromotive force. If no reversing switch is provided, one motor-armature switch may be opened, the motor-field circuit opened, and the rotating parts allowed to drop back slightly in speed, after which, first the armature switch and then the field switch may be closed, this process being repeated until, by chance, the machine comes up in correct phase relation. This operation, commonly known as *slipping poles*, is better performed if a synchronizer, or synchroscope, is installed for synchronizing the motor to the supply line. In this case, the procedure is as follows:

Having determined by the synchronizer on the generator that the generator electromotive force is 180 degrees out of phase with that of the running unit, connect the synchronizer of the motor, adjust the motor excitation for unity power factor, open the motor switch, and allow the motor to fall back in phase 360 electrical degrees, or 1 cycle, which will be indicated by one revolution of the needle of the synchronizer connected on the motor end. The motor switch must be closed at the exact instant of the in-phase position indicated by the vertical position of the synchronizer needle, and proper allowance must be made for the time element of the switch-operating mechanism.

In performing the operation of slipping poles when using a synchroscope, the motor, which is excited, after being disconnected acts as a generator, running by its own inertia, and must be synchronized very accurately. In order that its reduction in speed shall be small and its beat slow, the generator end of the unit should not be excited during the operation.

8. After the generator electromotive forces are thus brought into phase with one another, or approximately so, they should be equalized. The units may then be connected in parallel.

If the motor-generator already running is under load, the incoming machine will be out of phase, as in the preceding case, but by a different amount; full load on the running unit in this case causes displacement of the generator electromotive force by only about $12\frac{1}{2}$ degrees.

SYNCHRONOUS FREQUENCY CHANGERS ON STANDARD SERVICE

9. Phase Relations.—Synchronous frequency changers more commonly work between 25-cycle and 60-cycle systems, in which case the higher frequency is 2.4 times the lower. Such units are usually constructed with ten poles on the 25-cycle end and twenty-four poles on the 60-cycle end; and there is but one position of the rotor correct for paralleling, although there are five possible positions of correct phase relation when the unit is operating as a 25-cycle motor only, that is, one-half

the number of motor poles. The cause of this complication of phase relations can be shown, arithmetically, as follows:

Two 25-cycle–60-cycle frequency-changer sets are assumed to be in operation as 25-cycle motors without load and with the 60-cycle generator electromotive forces in phase, though, in order that the following operations may be performed, the generators cannot be in parallel. If one machine is slipped back one pair of poles, or 360 electrical degrees, or 1 cycle, on the 25-cycle end, the 60-cycle generator will slip back $60 \div 25 = 2.4$ cycles, or 864 electrical degrees. The electromotive force of this generator will then be $864 - 720$, or $.4 \times 360 = 144$ degrees out of phase with the electromotive force of the other machine; the generator has been slipped back 144 degrees more than 2 complete cycles. If the motor is slipped back another cycle, the generator electromotive force will slip back 864 electrical degrees more, making the total slippage of the generator 1,728 degrees, or 4.8 cycles. The electromotive force of the generator is then .8 cycle, or $.8 \times 360 = 288$ degrees, behind that of the other machine, or .2 cycle = 72 degrees ahead; the total slip has been .8 cycle more than 4 complete cycles and .2 cycle less than 5 complete cycles. Another slip will cause the generator to be 72 degrees behind in phase; the next, 216 degrees behind, or 144 degrees ahead; and the fifth slip will bring the generators back into phase again. There is only one relation that the motors may hold to each other for proper paralleling of the generators.

10. If the operation is inverted, that is, if the 60-cycle machines are motors and the 25-cycle machines are generating, slipping the 60-cycle motor back 1 cycle, or 360 electrical degrees, will slip the 25-cycle end back $360 \div 2.4 = 150$ electrical degrees. It would require twelve slipping operations to bring the generators again into phase, and there would be twelve possible relative motor positions, only one of which would be correct for paralleling the 25-cycle generators.

The phase displacements of generator electromotive forces, due to load on the running units, may be such as to cause considerable confusion. If the 25-cycle end is running as a motor

and under full rated load, the generator electromotive force will lag about $2.4 \times 25 = 60$ electrical degrees. If the motor is 20 per cent. overloaded, the phase displacement of the generator will be about 72 degrees.

11. Paralleling by Special Synchroscopes.—In one method of paralleling frequency changers transforming 25-cycle energy into 60-cycle energy, two synchronism indicators are employed. The indicator on the 60-cycle, or generator, end is provided with a dial marked as shown in Fig. 1. When the incoming motor is up to synchronous speed and its 60-cycle generator is excited, the pointer of the synchronizer on the 60-cycle end will take a fixed position, showing the operator how many pairs of poles on the 25-cycle end must be slipped to bring the generators into phase.

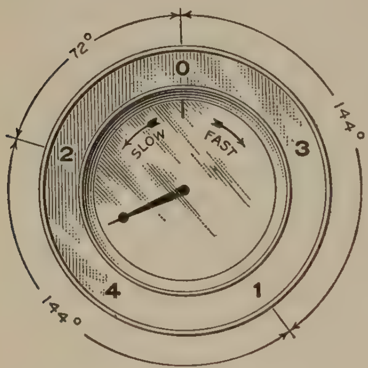


Fig. 1

For example, assume that the running unit is without load and that the pointer of the 60-cycle synchronizer stops at the figure *2* when the incoming motor has reached synchronous speed. The operator then proceeds to slip poles on the 25-cycle end of the incoming unit. He follows the method in the third paragraph of Art. **7**, slipping only one pair of poles at a time and synchronizing before slipping the next pair.

12. If the operating unit is about 20 per cent. overloaded and the incoming machine is without load, the needle of the 60-cycle synchronizer will come to rest in a position about 72 degrees ahead, in a clockwise direction, of its proper figure; that is, up to the next figure on the dial. Other relations between loads give other positions of the pointer. The indications thus given are easily misunderstood, and the resulting mistake of slipping the wrong number of pairs of poles can be avoided only by proper attention to the relative loads

on the two machines. The operator must always know the approximate percentages of full load that the units are carrying before attempting to parallel them.

Some synchronism indicators are provided with movable dials that can be set forwards by an amount depending on the load of the running machines.

13. If it is desired to parallel, by the pole-slipping method, two frequency changers in operation under separate loads, the generator synchronizer indications can be taken while the loads are connected, but the operator must give careful attention to the relative loads and interpret the synchronizer indications accordingly. The operator must also be familiar with the synchronizing connections. For example, if the more heavily loaded machine supplies current to the field winding of one type of synchronism indicator, the needle deflection will be clockwise from the figure indicating the number of slipping operations; if the more lightly loaded machine supplies current to the field winding of the synchronizer, the needle deflection will be counter-clockwise from the proper figure. After the correct synchronizer indication has been obtained, one of the machines is disconnected from its load, and the pole-slipping operation performed as previously described. Pole slipping cannot be performed on a frequency changer that is carrying a load.

14. The method of pole slipping described in Art. 7 is objectionable because of the necessity of using two synchronism indicators, and the necessity for extreme accuracy in synchronizing. In many frequency-changer installations, provision is made for slipping poles by inserting reversing switches in the field circuits of the motors. Each reversal of its field causes a synchronous motor to drop back in phase 180 electrical degrees. Each reversal of the field of the 25-cycle end of a motor generator changing 25-cycle energy into 60-cycle energy will therefore cause the 60-cycle generator to fall back in phase $2.4 \times 180 = 432$ degrees, or 1.2 cycles. A sufficient number of reversals will bring the generator electromotive force into the proper phase relation for paralleling. When this method of

pole slipping is used, the numbers on the 60-cycle synchronizer dial are arranged as shown in Fig. 2, no synchronism indicator being needed in connection with the 25-cycle, or motor, end.

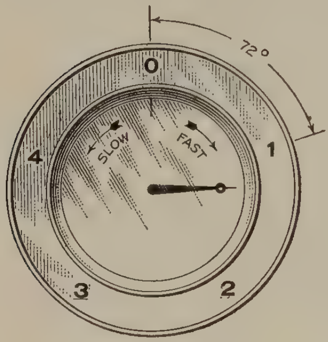


FIG. 2

15. When a 25-cycle–60-cycle, synchronous-motor-generator is started from the 25-cycle end, there is one chance in five that the 60-cycle end will come up in phase with a running unit; whereas, if started from the 60-cycle end, there is only one chance in twelve that the 25-cycle end will come up in phase. Such a motor-generator is therefore preferably started from the 25-cycle end, even though it is normally the generator end. No complications will arise when starting from the generator end; the generator will at once automatically assume its proper load as a generator.

However, conditions may be such that the start must be made from the 60-cycle end. A synchronizer intended for use on the 25-cycle end of a frequency-changer set and marked for indicating pole-slipping operations of the 60-cycle motor by the method of Art. 7 would have twelve points numbered at 150-degree intervals from the zero, or in-phase, position, bringing adjacent points 30 degrees apart, as shown in Fig. 3. The 25-cycle generator displacement due to full load on the 60-cycle motor will be about $25 \div 2.4 = 10.4$ electrical degrees. In this case, there is less opportunity for error, as the displacement at full load is only about one-third the distance between the numerals on the dial.

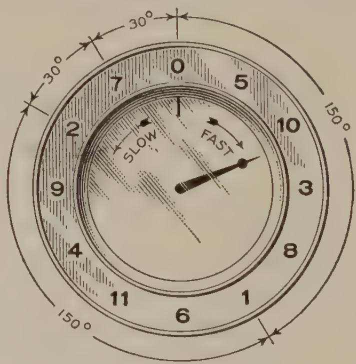


FIG. 3

16. Synchronism Indicator Dials.—In Fig. 4 is illustrated a synchronism indicator dial specially marked for paralleling 25-cycle–60-cycle synchronous motor-generators started from the 60-cycle end, which is, in this case, the motor end. One element of the synchronism indicator is connected to the generator of the machine running, and the other to the generator of the machine starting. Although the pole slipping is performed by manipulating the motor switches, the dial is marked to show the necessary slip in pairs of poles on the generator end, and the numbering of the dial, therefore, differs from that shown in Fig. 3. The number indicated by the pointer when the motor reaches synchronous speed represents the number of times the pointer should reach zero when the poles are slipped. For example, assume that the pointer stands at *3* when synchronous speed is reached. The motor switch is then opened, the machine begins to slow down, and the pointer revolves. The pointer is allowed to pass the zero position twice, but at the instant that it reaches zero the third time, the motor switch is closed, as the phase relations are then correct.

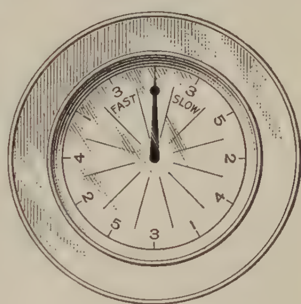


Fig. 4

17. Special Type of Synchroscope.—One type of special synchroscope used to secure proper phase relations at both ends of a 25-cycle–60-cycle synchronous motor-generator has two pointers, or hands, rotatable over the same dial. One pointer is acted on by synchronizing currents from the 25-cycle end; the other, by currents from the 60-cycle end. The 25-cycle synchronous motor is started by applying to its windings alternating current at a reduced voltage. When synchronous speed is reached, the 25-cycle hand on the synchroscope will point to the zero mark on the dial, and the 60-cycle hand will have a position depending on the phase relation between the 60-cycle electromotive forces of the running and incoming units. If the phase relation of the 60-cycle end of the incoming unit is correct

for paralleling, both hands will point vertically to the zero mark. If incorrect, the motor switch must be opened and the rotor of the set allowed to slow down. The two hands of the synchroscope will then begin to revolve at different speeds, the 60-cycle hand making 2.4 revolutions for each revolution of the 25-cycle hand. If the running unit is not loaded, there will be an instant when both hands point to the top of the dial, zero mark, at the same time, and at this instant the operator closes either the generator switch or the motor switch. Then, as soon as the other switch is closed, the incoming machine is properly paralleled with those already in service, and auto-

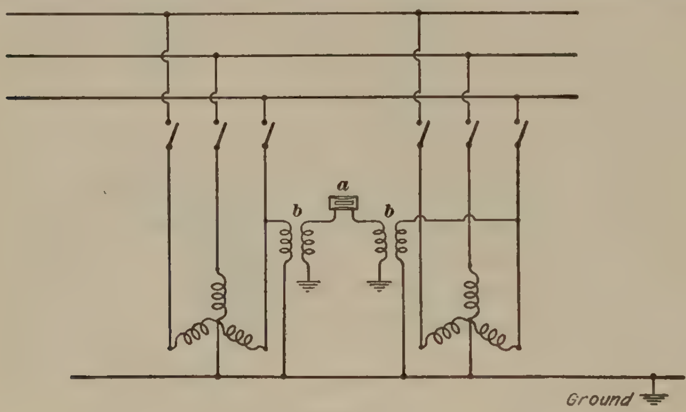


FIG. 5

matically takes its proper share of the load. If the running unit is loaded, the indicating hand actuated by its generator current will be in a position at one side of the zero mark at the moment for synchronizing, the divergence depending on the load.

18. Paralleling by Voltmeter and Chart.—In case the generator synchronizer of a frequency-changer set is disabled or otherwise unavailable, an alternating-current voltmeter connected to show at one reading the difference in voltage between the incoming and running generators can be used. In Fig. 5, the voltmeter *a* is connected between the secondaries of potential transformers *b*, the primaries of which are connected between phase terminals of the three-phase Y-connected alternators

of the motor-generator sets. In this case, the neutral points of the alternator-armature windings are connected together through a grounded neutral bus. If the voltages of the two generators are adjusted separately to the same value, the reading of the voltmeter *a* will depend on the phase relation between the two electromotive forces.

19. In Fig. 6 is shown a chart prepared for use in paralleling 60-cycle, three-phase, 2,200-volt, star-pressure, alternators

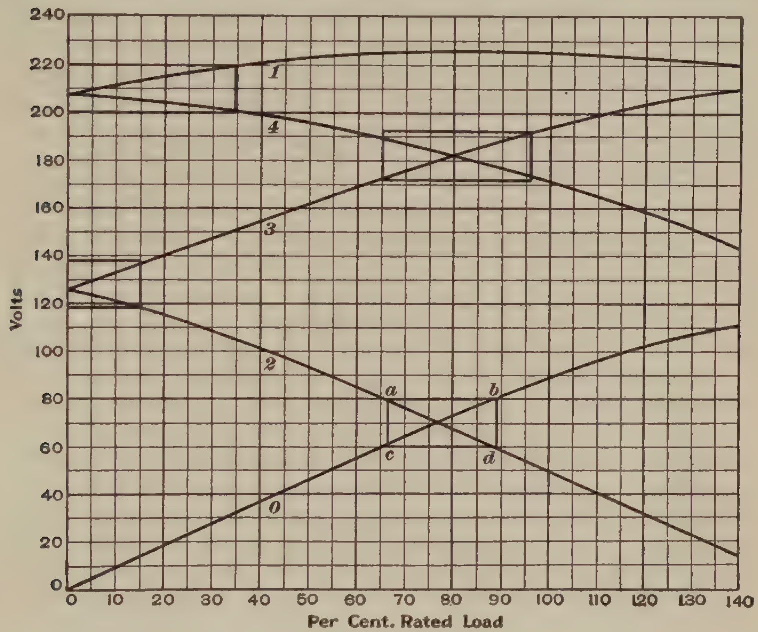


FIG. 6

driven by 25-cycle synchronous motors. The chart shows the voltage differences between the 60-cycle alternators of the motor-generator sets at various loads and in different phase relations. The vertical scale represents volts difference between generators, and the horizontal scale, the percentage of rated load on the running unit. The curves marked *1*, *4*, *3*, *2*, and *0* represent the number of pairs of poles to be slipped on the

25-cycle motor when the operation is performed by the use of the motor switch and the 25-cycle synchronizer, as in Art. **7.**

20. To use the chart, the voltages of both generators, running and incoming, are adjusted to 2,200, and the reading of a voltmeter connected as in Fig. 5 is observed. The percentage of full load on the running machine is then determined by observation of the ammeter or wattmeter. The vertical line beginning at the number representing the observed per cent. rated load is then followed on the chart to the point of intersection with the horizontal line representing the reading obtained from the voltmeter. The curve *0*, *1*, *2*, *3*, or *4* that is nearest the intersection indicates the number of slipping operations necessary; and, owing to the manner in which the curves are prepared, the intersection will always be close to one of the curves.

If the intersection of the vertical line with the horizontal line falls within one of the rectangles at the curve intersections, the indication is uncertain and should not be relied on until one pair of poles has been slipped and another observation taken. The two observations together enable the operator to determine the proper number of slips to be made. For example, a running unit is assumed to be carrying 100 per cent. rated load. The voltages of the incoming and running generators are each regulated to 2,200, and the reading of the voltmeter, connected as shown in Fig. 5, is 58. The intersection of the vertical line at 100 with the horizontal line at 58 is near the curve *2*; hence, two pair of poles must be slipped. Again, the running unit is assumed to be carrying 80 per cent. of rated full load, and the voltmeter indication to be 70. Referring to the chart, the vertical line through *80* intersects the horizontal line through *70* at a point within the rectangle *a b c d*, and it is indeterminate whether the generators are in the correct phase relation for paralleling, or whether two pair of poles must be slipped. In order to get a definite observation, the motor is slipped one pair of poles. If the generators had at first been in proper position for paralleling, there will be four slips necessary and the voltmeter will indicate approximately 182 volts. If, however, the phase relation at first had been such that two slips were neces-

sary, only one will remain to be made, and the voltmeter would show in the neighborhood of 220 volts.

21. A chart similar to that shown in Fig. 6 can be made for use with other synchronous-motor-driven frequency changers converting 25-cycle energy into 60-cycle energy. One unit is run unloaded in each of the five possible phase positions successively. Another unit is run under various loads ranging from no load to 20 or 30 per cent. overload for each of the phase positions of the unloaded unit. The reading of a voltmeter connected as in Fig. 5 is observed and recorded for each condition, and the values of volts and per cent. rated load are laid off and curves plotted as in Fig. 6. The voltages of the generators must be kept constant and equal throughout the test. Afterwards, when using the chart, the generator voltages must be brought to this value, or the chart values must be multiplied by the proper correcting factor.

22. Conditions for Parallel Operation.—To be operated in parallel synchronous-motor-generators must be constructed alike, so that when the motors are rotating synchronously the generators will be exactly in phase with one another. The alinement of both the rotating and the stationary parts of the 25-cycle end with those of the 60-cycle end should therefore be precisely alike on all machines to be operated in parallel.

Even with correct alinement, an error in connections may cause an unsatisfactory division of load between units. Corresponding poles of all parallel connected motors and corresponding poles of all parallel connected generators of such sets must have like polarity. The relation of the connections of the motor armature leads is not important, but corresponding terminals of the generator armature windings must be connected to the same phase conductors of the busses.

23. Control of Power Factor and Current Load.—The power factor of the synchronous motor of a frequency-changer set is regulated in the same manner as though the motor carried a purely mechanical load. The current loads between paralleled generators of frequency changers are controlled in the same manner as for any alternators connected in parallel.

A unit to be disconnected should be relieved as much as possible of the current load by means of the generator rheostats before the armature switch is opened.

24. Control of Kilowatt Load.—The distribution of kilowatt load among synchronous frequency changers in parallel is ordinarily beyond the control of the operator. An incoming unit, on being connected in parallel with a running unit, at once takes a definite proportion of the load, and no manipulation of exciting currents will change this proportion more than 1 or 2 per cent.

In general, a synchronous-motor-generator that is to carry more or less than its proper proportion of the kilowatt load

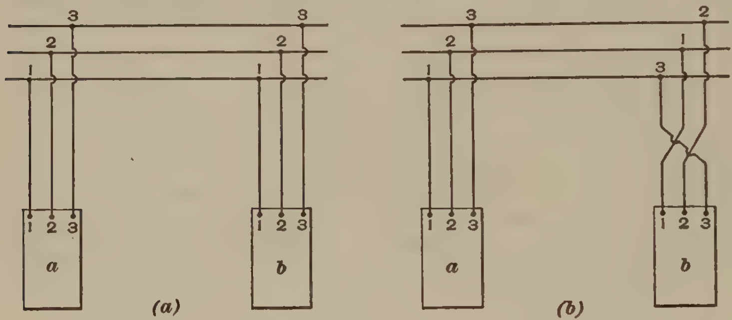


FIG. 7

must be so manipulated as to cause it to lead or lag in phase relative to the machines in parallel with it. The manipulation consists in properly changing the connections of the generator armature leads, reversing the generator field leads, and slipping poles.

25. In Fig. 7 (*a*) are shown two generators *a* and *b* of synchronous-motor-generators properly connected for correct-load division; like terminals of the generators are connected to the same bus-bar, as indicated by the numerals. In (*b*) the leads of the generator *b* are shifted so as to change the phase relation of the machines by 120 degrees. Such a shift, or transposition, is called *spiraling* the leads, and is sometimes made in order to obtain a desired load division.

26. Assume that the leads of the 60-cycle generator of a synchronous-motor-generator converting 25-cycle energy into 60-cycle energy are spiraled at the generator terminals or somewhere between the synchroscope connections and the generator terminals so as to advance the phase position of the generator by 120 degrees. Slipping one pair of poles on the motor will cause that generator to lag 144 degrees behind its former phase position, the net result of the spiraling and pole slipping being to cause the generator to lag 144 − 120 = 24 degrees behind the others. A reversal of the generator field polarity will cause a further change of 180 degrees

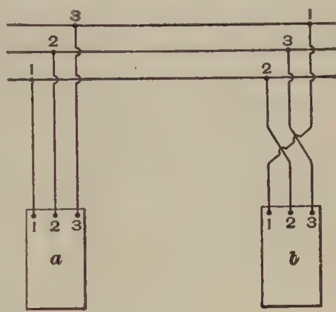


FIG. 8

TABLE I

METHOD OF OBTAINING PHASE CHANGES IN SYNCHRONOUS-MOTOR-GENERATOR OPERATION

Generator Leads	Slip Generator Degrees	Generator Fields	Angle of Lead Degrees	Angle of Lag Degrees
Spiral forwards	288	Reverse	12	
Spiral backwards	216	No change	24	
No change	144	Reverse	36	
Spiral forwards	72	No change	48	
Spiral backwards	None	Reverse	60	
Spiral backwards	72	Reverse		12
Spiral forwards	144	No change		24
No change	216	Reverse		36
Spiral backwards	288	No change		48
Spiral forwards	None	Reverse		60

in its phase position, leaving it 180 − 24 = 156 degrees ahead of the others. By again slipping one pair of poles, 144 degrees of

this phase difference can be removed, leaving the generator 156 − 144 = 12 degrees ahead of the others.

In like manner, the phase relations can be changed by any desired multiple of 12; the procedure is as follows: The generator leads can be spiraled either forwards, as in Fig. 7 (*b*), or backwards, as in Fig. 8; the generator field can be reversed, and the generator can be slipped back by multiples of 72 degrees by slipping poles on the motor. The simplest method of securing a slip of 72 degrees on the generator end is to reverse the field on the motor end.

Table I shows the method of obtaining any desired phase difference in multiples of 12 degrees from a lag of 60 degrees to a lead of 60 degrees. In practice, it will seldom be necessary to use all the changes shown in the table.

27. Some synchronous-motor-generators are so constructed that the stationary, non-rotating member of either the 25-cycle end or the 60-cycle end is mounted in a cradle in which it may be rocked through a few degrees to obtain a phase displacement. This style of construction permits of a much finer adjustment than can possibly be obtained by the method previously described.

SYNCHRONOUS CONVERTERS

PRELIMINARY INSPECTION

28. Before starting a synchronous converter for service, the condition of the commutator and of the brush contact with the commutator and with the collector rings should be noted. Dirt, copper particles, dust, and all other foreign objects should be removed from the machine. Knife-blade switches should be examined for poor condition of contacts.

STARTING FROM SPECIAL TRANSFOMER TAPS

29. The simplest method of starting a synchronous converter is to apply to the armature a reduced voltage taken from portions of the secondary windings of the main transformers. Usually, about one-third normal alternating-current voltage is applied first, followed by two-thirds voltage, and then by full voltage. The field circuit is left open and the field winding is divided into open-circuited sections until the armature reaches synchronous speed. The reduced voltages for starting are usually obtained by means of two three-pole, double-throw switches connected as shown in Fig. 9.

30. Assuming that the machine is provided with a quick-break field switch, not shown in Fig. 9, the procedure for starting is as follows:

Open the field switch and also the field-break-up switch on the frame of the machine. See that the armature circuit is open on the direct-current end. Close the starting switch *a*, Fig. 9, to the upper position. Close the other starting switch *b* to the upper position. Close the primary switch (oil switch) connecting the transformers to the high-tension, alternating-current bus-bars. The armature will then begin rotation, and will reach synchronous speed in a few seconds, the time depending on the size of the armature and on the voltage applied to the armature windings.

When the armature has reached synchronous speed, observe the polarity of the machine by connecting the voltmeter (not shown) to the direct-current terminals, using, if possible, the switchboard instruments and connections. If the polarity is correct, close the field switch; then close the field-break-up switch into the running position, the upper position in Fig. 9. If the polarity is incorrect, as indicated by a reversed indication of the voltmeter, close the field switch and then the field-break-up switch in the lower position. Carefully observe the voltmeter; the voltage will decrease to zero and reverse. At the instant that the voltmeter needle passes over the zero point, reverse the field-break-up switch, closing it into the running position.

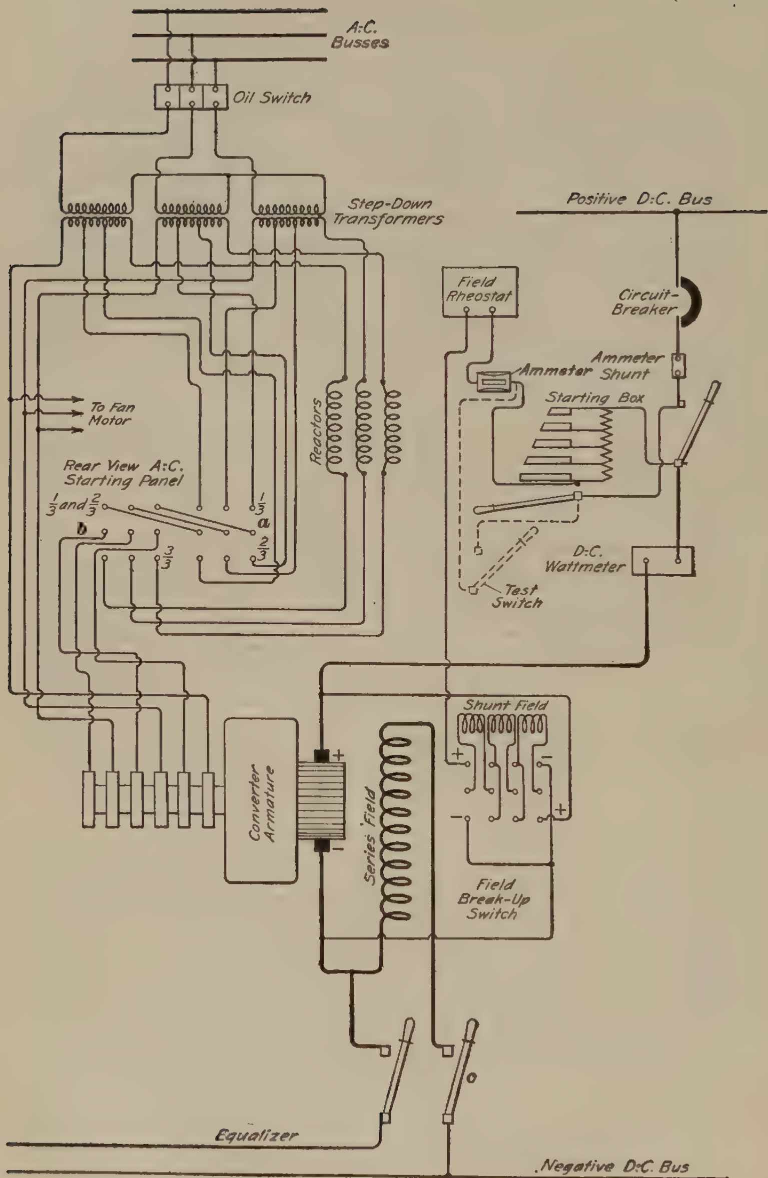

A.C. Busses
Oil Switch
Step-Down Transformers
Positive D.C. Bus
Field Rheostat
Circuit-Breaker
Ammeter Shunt
Ammeter
Starting Box
To Fan Motor
Reactors
Rear View A.C. Starting Panel
1/3 and 2/3
1/3
a
b
2/3
3/3
D.C. Wattmeter
Test Switch
Shunt Field
Converter Armature
Series Field
Field Break-Up Switch
Equalizer
Negative D.C. Bus

FIG. 9

When the polarity is correct and the field switches are closed, throw the starting switch *a*, Fig. 9, quickly to the two-thirds, or lower, position. In 4 or 5 seconds, increase the applied voltage to normal by throwing switch *b* quickly to the lower position.

STARTING BY INDUCTION MOTOR

31. A synchronous converter may be provided with an induction motor on an extension of the shaft. The motor is used exclusively for starting purposes and may be supplied either from a special set of transformers or from the main transformers that supply the converter. Assuming the latter condition, the procedure for starting is as follows:

See that the switch in the secondary circuit between the transformers and the armature of the synchronous converter is open. Close the field switch of the converter, the transformer primary switch, and the starting switch of the induction motor. The machine will then start; when it is running at a speed slightly greater than normal, connect the synchronizing circuit, and open the starting circuit of the induction motor. As the speed of the machine becomes slower, watch the synchronizing devices, and when synchronism is indicated close the switch connecting the armature of the converter to the transformer secondaries.

If no synchronism indicating circuits are provided, the procedure is changed. Start by means of the induction motor, as before; but leave the field and field-break-up switches of the synchronous converter open. When the machine is up to speed, open the induction-motor switch and close the switch connecting the converter armature to the transformer secondaries. Observe the polarity of the direct-current electromotive force and correct it, if necessary, as described in Art. **30.**

STARTING WITH DIRECT CURRENT

32. When started as a direct-current motor, a synchronous converter must be synchronized to the alternating-current supply in the same manner that one alternator is paralleled with another. The procedure varies somewhat according to the

system of connections. First will be considered the case of a synchronous converter excited from the direct-current busses and not provided with a switch between the transformer secondaries and armature. Instead of the connection between the field ammeter, Fig. 9, and the lower clip of the starting box, substitute the current path through the test switch as indicated by the dotted line.

Close the field-break-up switch in its running, or upper, position. Close the test switch shown by the dotted lines and also close switch *c* and the circuit-breaker. Cut out nearly all of the resistance in the field rheostat and test the fields for excitation by applying a piece of iron to one of the pole pieces. Close the starting switch to the first clip, which places all of the starting resistance in the armature circuit. The armature will now begin to rotate. Observe the direct-current ammeter; when its needle has stopped, or nearly stopped, and is dropping back toward the zero position, cut out another section of the starting resistance, and proceed in this manner until all of this resistance is cut out of the circuit. Connect the synchronism indicating device, synchroscope, lamps, or voltmeter in circuit, and, by means of the field rheostat, regulate the speed of the machine until synchronism is reached. When the speed is correct, close the transformer primary switch at the instant that the two alternating electromotive forces are in phase with each other as indicated by the synchronizing device.

33. If provision is made for synchronizing with a secondary instead of a primary switch, proceed as follows: With the secondary switch open, close the transformer primary switch and start the synchronous converter, as described in the preceding article. Connect the synchronism indicating device; regulate the speed by means of the field rheostat to obtain a proper beat; and close the secondary switch when the electromotive forces are in phase.

34. In some installations, the converter field switch connects to the direct-current armature leads instead of to the bus. In this case, the switching procedure is the same as just described,

but the operator cannot test field excitation before connecting the armature circuit.

35. Split-pole synchronous converters, that is those having auxiliary regulating poles, require treatment slightly different from others. They are started with the main field excited to nearly full strength and no excitation of the auxiliary fields.

After the starting resistance is all cut out, regulate the alternating-current voltage of the machine to approximately that of the supply by adjusting the rheostats of the main and auxiliary fields. Strengthening the auxiliary field current in the same direction as the main field current reduces the alternating-current pressure, and reducing the auxiliary field current, or causing it to oppose the main field current, increases the alternating-current pressure. When the alternating electromotive force of the machine is approximately equal to that of the supply, regulate the speed of the machine by means of the main field rheostat as much as possible, and by means of the auxiliary fields when necessity demands it. When the speed is correct, adjust the auxiliary and regulating fields again to equalize the alternating electromotive forces. Considerable adjustment of both main and regulating field rheostats is sometimes required in order to regulate both speed and pressure. After this is done, the machine should be synchronized in the usual way.

COMBINATION METHOD OF STARTING

36. A synchronous converter can be started by combining the direct-current and alternating-current methods. The advantage of so doing is that no synchronizing operations are necessary.

Start the machine as a direct-current motor. When all the starting resistance is cut out, open the armature circuit and then open the field circuit by means of a quick-break field switch with a discharge resistance; immediately connect the alternating-current supply to the armature at the lowest available pressure. If secondary switches connected to different transformer taps are provided, proceed to increase the applied alternating-current pressure by the method explained in Art. **30.**

If no such switches are provided, connect the full supply potential to the armature when it is rotating at approximately full speed. If the field switch connects to the armature direct-current leads, correct the polarity, if it is incorrect. If the field circuit connects to the load direct-current busses, close the field switch and close the reversing field-break-up switch to the running position. If the polarity is reversed, it will be corrected when the fields are thus excited from the busses in the proper direction.

Another method of correcting polarity is available when paralleling a compound-wound synchronous converter to one or more similar units carrying considerable load. In this case, the shunt-field circuit of the incoming machine is left open, the equalizer switch and the armature switch of the same polarity are closed, and the armature switch of opposite polarity is left open. A part of the current of the other machines follows the path through the series winding of the incoming unit and corrects the polarity. The shunt-field circuit is then closed. This operation is best performed when the converter is running on the low-pressure connections.

SINGLE OPERATION

37. Synchronous converters employed in electric-lighting systems, especially if used in parallel with storage batteries, are usually shunt wound. To operate a shunt-wound machine separately, if the direct-current busses are dead, proceed as follows: Having started the machine and corrected the polarity, regulate the direct-current voltage to normal and close the armature switches to the direct-current busses. If these busses carry considerable load at the time the machine is connected in, the voltage will decrease a little but can be brought back to normal by whatever means is provided for voltage regulation.

The same procedure applies to the operation of a single compound-wound synchronous converter for railway service, except that the load, unless excessive, will not cause much, if any, drop in the direct-current voltage.

PARALLEL OPERATION

38. Assume that a shunt-wound synchronous converter is to be operated in parallel with other sources of direct current, as storage batteries, shunt generators, or other shunt-wound converters. After starting the machine regulate the direct-current voltage to equal that on the bus-bars, and close the main armature switches to the busses. Divide the load among the machines as desired. A synchronous converter is caused to take load by raising its terminal voltage and to drop load by the reverse process.

Compound-wound synchronous converters are connected in parallel in the same manner as compound generators; that is, by the use of equalizing connections for their series-field circuits. In paralleling such units, the equalizer switches are closed and then, on the incoming unit, the armature switch having the same polarity as the equalizer connections. After this is done, the converter pressure and that of the bus-bars, are equalized, after which the other armature switch should be closed.

Ordinarily, compound-wound rotary converters must not be connected in parallel with storage batteries, shunt-wound generators, or shunt-wound rotary converters. If, however, there is a long length of feeder between the compound machine and the battery, or the shunt machine, so that the drop in the feeder is equal to the compounding effect, they may be operated in parallel.

VOLTAGE REGULATION

39. The direct-current voltage regulation of synchronous converters is usually obtained by means of potential regulators connected in the alternating-current leads; by means of series synchronous boosters, sometimes called *synchronous booster converters;* and by means of regulating poles, or split-pole windings. Two other methods, by direct-current boosters and adjustment of field excitation, are not much used.

Voltage regulation by means of a potential regulator is produced by rotating the primary winding of the regulator into different positions with respect to the stationary secondary

winding. This is done either by the use of a hand wheel or an alternating-current motor geared to the rotating shaft of the regulator primary winding, the rotation of which in one direction lowers the alternating-current pressure applied to the armature and consequently lessens the direct-current pressure of the converter; rotation in the other direction raises the pressure.

Voltage regulation by means of series synchronous boosters is carried on by the use of the field rheostats in the main field circuits of the rotary converter and the booster. In this case, practically all the pressure regulation is done by means of the booster; but it is necessary to adjust the main field rheostat, also, in the regulation of the power factor.

Synchronous converters having regulating poles are regulated by varying the wave form of the alternating current in the armature. It is done entirely by adjusting the main and auxiliary field rheostats.

INTERRUPTION OF ALTERNATING-CURRENT SUPPLY

40. If the alternating-current supply to a synchronous converter operating alone is interrupted, the machine will stop. If, however, the synchronous converter is operating in parallel with direct-current generators, storage batteries, or synchronous converters having an uninterrupted supply, the converter on the interrupted circuit may run inverted, receiving energy from the direct-current bus, and may appear to be operating normally. A synchronous converter may also run inverted, because of too low transmission-line pressure. In either case, the inversion is indicated by a reversed reading of the direct-current ammeter.

To determine whether the inversion is due to interrupted supply or to low transmission-line pressure, strengthen the field of the inverted machine. If the amount of inversion, or back feed, is thereby reduced and the speed of the machine is not diminished, the indication is that the machine is still running synchronously and the supply is uninterrupted. If, however, strengthening the field causes a reduction in speed and the amount of back feed is reduced for only 2 or 3 seconds, the

transmission supply is probably interrupted. As long as a rotary converter is operating inverted, the alternating-current voltmeter indication is not a reliable means of determining whether the transmission-line supply is interrupted, because the alternating-current circuit is kept alive by the inversion.

If the test shows the supply to be interrupted, the synchronous converter should be disconnected from the alternating-current busses at once; because, if the transmission line were to be made alive with the inverted converter connected, the machine would probably be seriously damaged, having fallen out of step.

41. If a synchronous converter with very weak field excitation is operating in parallel with other sources of direct current, an interruption of the alternating-current supply may be followed by excessive speed of the machine, now motorized on the direct-current side. In such an emergency, the speed-limit device should immediately open the direct-current circuit-breaker; if it does not, the operator should at once either strengthen the fields or open the direct-current armature circuit.

If an inverted synchronous converter, even when normally operating with a strong field excitation, feeds back into a circuit taking lagging current, this current may weaken the converter field enough to cause the armature to speed up dangerously. For this reason, whenever it can be avoided, induction or even synchronous motors should not be operated on the same line with synchronous converters that feed to direct-current busses having other sources of supply.

Synchronous converters operating in parallel with some other source of direct current at a time when a severe short circuit occurs on the alternating-current line may invert or back feed from the direct-current bus and supply alternating current to the short circuit, even after the line oil switch at the generating station has opened. If, in such cases, reverse-current or overload relays do not automatically disconnect the inverted units, the oil switch of each rotary converter should be opened at once by the operator.

POWER FACTOR

42. The regulation of the power factor of a synchronous converter, like that of a synchronous motor, is effected by changing the exciting current. Machines built with regulating poles require regulation on both main and auxiliary fields, as do also converters with series synchronous boosters.

A synchronous converter operating with a low power factor may become fully loaded, or even overloaded, when the direct-current ammeter indicates less than the normal current rating, or when the output is less than the unit is rated for. If the synchronous converter is provided with an alternating-current ammeter, the operator should observe it frequently and carefully, as it indicates the actual load on the unit. If the power factor is low, the direct-current meters or the alternating-current wattmeter may lead the operator into serious error, if he relies on their indications alone. If no alternating-current ammeter is provided, the current can be calculated from readings of the alternating-current wattmeter and the power-factor indicator.

A synchronous converter should be operated, as near as possible, at unity power factor and at full load. Shunt-wound and compound-wound machines with the series-field cut out or short-circuited should take a leading current at no load, so as to give unity power factor with load. A compound-wound machine should take a lagging current at no load.

MISCELLANEOUS EQUIPMENT

STORAGE BATTERIES

FLOATING

43. In electric stations and substations, storage batteries are used in two distinct classes of service: *Peak-load service*, in which they are charged at times of light load and discharged during heavy-load periods; and *emergency*, or *stand-by*, *service*, for which they are kept charged and ready for immediate discharge in case of any interruption of the regular direct-current output from generators or synchronous converters.

When neither charging nor discharging, a storage battery can be disconnected from the bus-bars or it can be floated on them. In order that a battery may float on the busses its pressure must be regulated to equal the bus-bar voltage. Although a floating battery may charge and discharge in small amounts, taking care of the fluctuations in demand and supply, the battery remains available for practically its full rated duty. Under such conditions the battery performs a third service, that of steadying the bus voltage and the load on the station machinery.

44. Considerable care must be taken to see that floating is done properly. If the battery pressure is even slightly higher than the bus voltage, the discharge will be greater than the charge and the battery capacity immediately available will be gradually reduced. The usefulness of the battery for peak load or emergency service is thus diminished and the generating machinery is not materially relieved. Also, where end cells are used to regulate the battery voltage, some of the cells will be discharged less than the others. If the battery voltage is

too low for correct floating there will be a net charge, which, though harmless, is not economical.

45. Correct Floating Voltages.—The correct floating voltage per cell depends on the type of cell; the proper value for a given type is generally specified by the manufacturers,

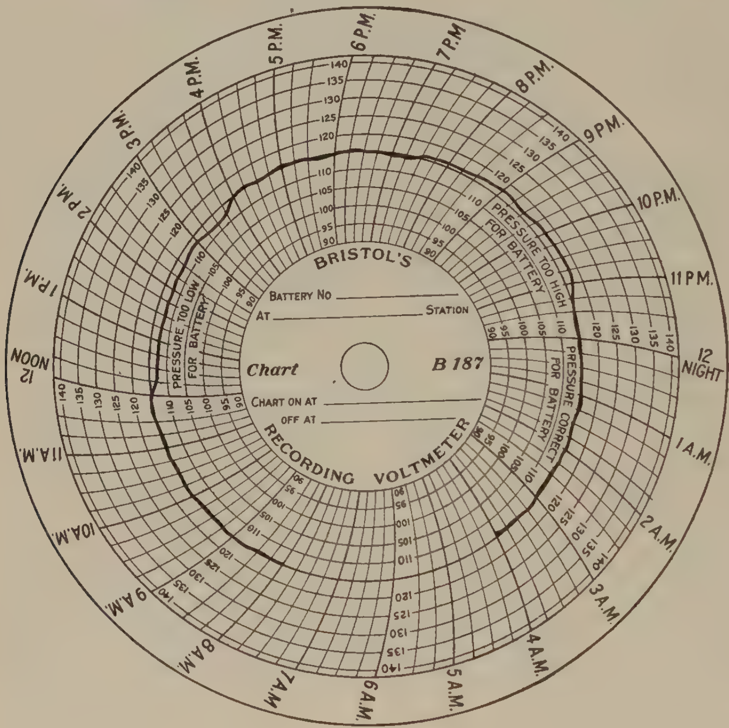


FIG. 10

and may lie between 2.08 and 2.12 when the battery is fully charged. To keep a battery floating in the fully charged condition, its voltage must be changed to meet changes in the bus-bar voltage. When the battery voltage is regulated by means of end cells, equality of bus-bar and battery voltage cannot be maintained exactly without changing the bus-bar voltage.

If the battery is to float in a partly discharged condition, the floating voltage per cell must be determined from a discharge curve, because the voltage of a cell diminishes as the discharge progresses.

Lacking knowledge of the proper floating voltage, the operator must rely on the indications of an ammeter or ampere-hour meter in the battery circuit.

Precise floating can usually be obtained on lighting systems; on railway systems the load and bus voltages are generally so variable that the floating is only approximately correct.

46. Checking Floating Regulation.—The method of regulating the floating by cell pressures should be checked by observing the indications of the recording voltmeter and the ampere-hour meter, and by testing the specific gravity of the electrolyte in the pilot cell. The recording voltmeter should be so marked, or calibrated, as to indicate clearly the condition of correct floating, and it should be connected across a considerable number of cells, else its indication will be unreliable. The chart shown in Fig. 10 is printed with the correct floating voltage indicated by a heavy-line circle with which the wavy line traced by the voltmeter needle coincides when the battery is floating properly. On the actual chart, which is about twice as large as that shown in the illustration, the voltmeter indication is traced in red ink and the printed voltage circle is a black line heavier than the other circles.

DISCHARGE

47. A storage battery is caused to discharge by raising its voltage relative to that of the bus, and the amount of discharge is controlled by regulating the relative increase, as explained in *Storage Batteries*.

48. If, at any time, during discharge, the number of ampere-hours already delivered is known, the length of time during which the battery can be further discharged at a given rate can be determined by reference to a set of curves similar to those

shown in Fig. 11, which is drawn for a battery capable of delivering 1,060 amperes for 1 hour. The heavy-line curve is called the *capacity curve;* each of the broken-line curves represents the discharge, in ampere-hours, that has already taken place. For example, let it be assumed that the battery has been discharged for 30 minutes at a rate of 800 amperes and that the

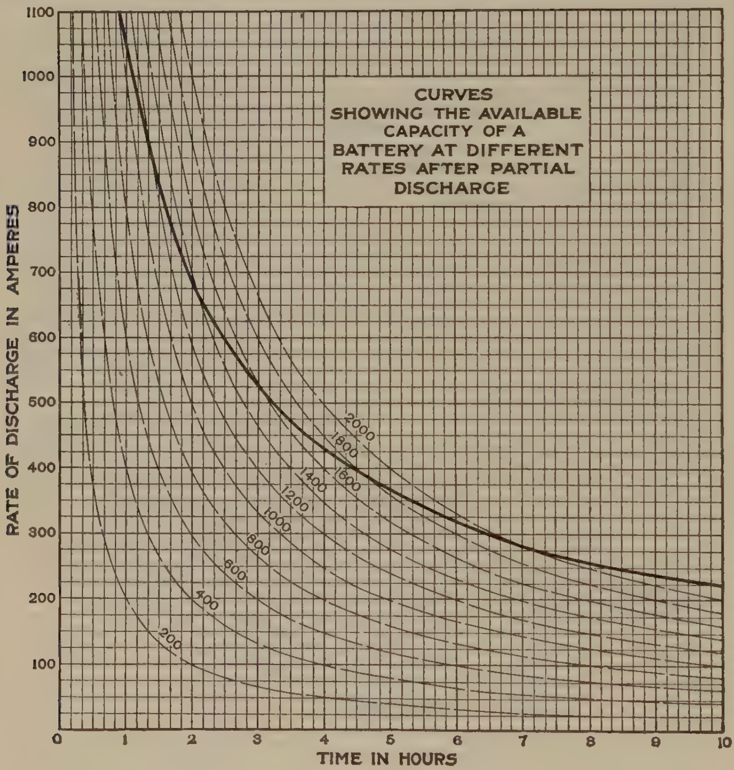


FIG. 11

operator wishes to know how much longer the discharge can continue at a rate of 600 amperes. The number of ampere-hours already discharged is $\frac{800\times 30}{60}=400$. The 400-ampere-hour discharge curve, marked *400*, is followed to its intersection with the horizontal line corresponding to the rate,

600 amperes, to be carried. The desired time interval is then found by measuring on the horizontal scale the distance between the intersection just found and the intersection of the rate line, 600, with the capacity curve. The first-named intersection is at a point corresponding to about 40 minutes on the horizontal scale, and the second-named intersection at a point corresponding to nearly 2 hours and 30 minutes. The battery can therefore carry a load of 600 amperes for 2 hours and 30 minutes less 40 minutes, or 1 hour and 50 minutes, approximately.

49. When a battery is subjected to a very long and heavy discharge, some of the cells may be completely discharged and reversed in polarity. When the battery is again charged, these cells will be again reversed, thus making their polarity correct; but when the remaining portion of the battery is fully charged, the cells that were reversed will be only partly charged. In order to complete their charge, the undercharged cells should be connected to a low-voltage supply and charged separately.

CHARGING

50. After a battery is discharged, it should be given the regular charge as soon as operating conditions will permit. This charge is usually given at the normal rate, which can be increased if the charge must be hastened.

In lighting, power, and railway service, the regular charge is usually carried on at constant current. The curve of the recording voltmeter should be watched during the charge, as it shows, in a general way, the state of the charge. There will be, first, a sharp rise in pressure, as at *a*, Fig. 12, followed by a long, steady rise until the voltage per cell reaches a maximum, at which point the cells, if in good condition, will begin to gas rather freely. The recording voltmeter curve will then take a steeper rise until the pressure required to maintain the constant charging rate becomes constant, as at *b*. The charge should be continued at this constant pressure for about 15 minutes and then stopped. End cells that were discharged a shorter time than the main battery will become fully charged

before the others, and should be cut out of circuit as soon as they have been gassing freely for 15 minutes.

The specific gravity of the acid increases during charge until it reaches a maximum and constant value when the cell is completely charged. Hydrometer readings of a cell in good condition, therefore, serve as indications of the state of charge.

51. Batteries that are not regularly discharged are subject to a reduction in capacity due to local action if kept on open

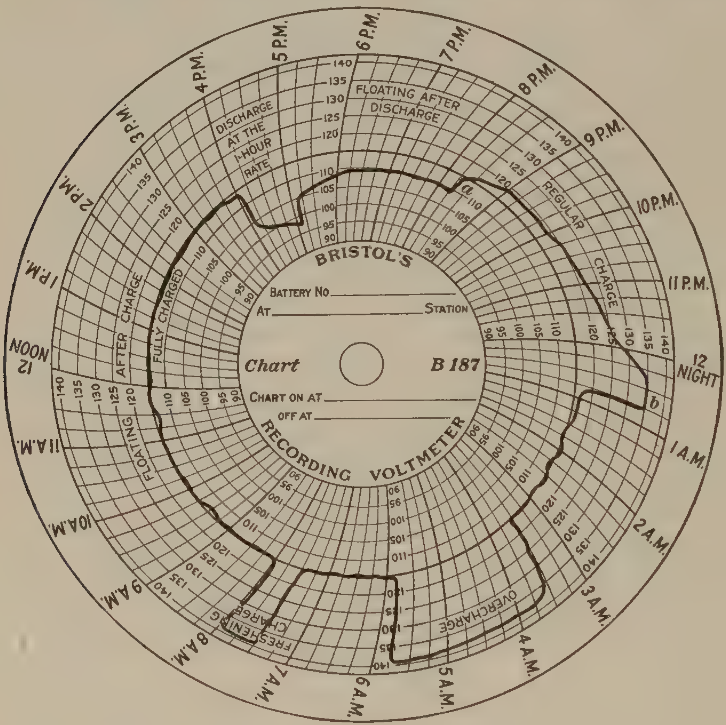


FIG. 12

circuit, or if floated at too low a voltage. When a battery has not been discharged and recharged for a considerable time, as 10 days or 2 weeks, it should be given a freshening charge to restore the cells to a normal and uniform condition. All the cells should be in circuit and the charge should be continued

until the cells gas freely and the charging voltage, with a constant current rate, remains constant for 15 minutes. If the battery is subject to a slight net discharge during floating, the freshening charge should be more frequent, once, or even twice, a week.

52. Formed-plate batteries should have an overcharge at intervals of 2 or 3 weeks if they have had no regular charge. In overcharging, the charging voltage is maintained constant for 1 or $1\frac{1}{4}$ hours.

53. Fig. 12 shows a recording voltmeter chart giving voltage records for floating a battery fully charged, a discharge at the 1-hour rate, floating after discharge, regular charge after a discharge, overcharge, and a freshening charge. The last two would not occur on the same day as a discharge and regular charge, but all are shown together for comparison.

SERIES BOOSTER GENERATORS

54. Direct-current generators used as boosters are connected in series between the direct-current supply (generator, synchronous converter, or storage battery) and the load. The method employed in putting a series booster generator into service varies according to the arrangement of the connections; the following is the common procedure for boosting feeders: Close the switches *a* and *b*, Fig. 13, connecting the booster generator to the bus and the feeder, respectively. The booster terminal connected to the bus must have a polarity opposite that of the bus. Open the feeder switch *c*, start the booster motor, not shown, and manipulate the field rheostat of the booster generator until the correct voltage on the feeder is obtained. When

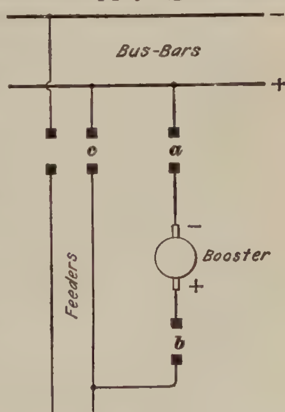


FIG. 13

shutting down the booster, reverse the process; reduce the booster voltage, stop the motor, close the feeder switch, and disconnect the booster.

TRANSFORMERS

55. Large transformers in electric stations or substations are generally provided with primary and secondary switches and instruments. If properly adapted for multiple operation, they may be connected in parallel, either for transfer of load from one to the other, or for regular operation.

When putting large transformers into service, it is better to close, first, the switch connecting the transformer to the supply and then the one connecting the load to the transformer. In this way, the momentary rush of current is lessened.

Transformers cooled by air blast must not be operated without a continuous supply of air. If a transformer is under full load, an interruption of air blast for only a short time may result in overheating sufficient to damage the insulation to the breaking-down point or in permanently injuring the steel core. If the transformer is cooled by water circulating in coils of pipe submerged in oil, the same rule applies. Every effort should be made to put disabled cooling apparatus into condition as soon as possible.

POTENTIAL REGULATORS ON DISTRIBUTING CIRCUITS

56. The voltage regulation of an alternating-current circuit for local distribution from a generating station or a substation is accomplished by means of a potential regulator connected in series with the circuit. An automatically operated potential regulator should occasionally receive attention to see that it is maintaining the correct pressure on the circuit. If line-drop compensators are not used, the operator should have either a curve or a schedule showing the proper voltage for each load on each circuit, in order that he can check the performance of the regulators.

Non-automatically operated potential regulators require closer attention from the operator, who should be careful that the step-by-step action of a regulator of the variable-transformer type is positive and complete each time. Manipulation of the hand lever should be performed with a loose-wrist movement so as not to retard the quick-jump action of the dial switch.

CARE AND MAINTENANCE OF ELECTRICAL MACHINERY

GENERAL INSTRUCTIONS

INSTALLATION

57. Unpacking and Handling.—Large machines, too heavy to handle complete, are shipped in sections, which are assembled at their destination, usually by the erecting department of the manufacturer, and always according to the manufacturer's instructions. The following general remarks on installation apply more particularly to machines of small or moderate size shipped completely assembled.

During unpacking and handling, machines or parts should be carefully protected from severe shocks or blows. The eyebolts, or bails, when provided, should be used for lifting the machines, if possible. Great care should be exercised in handling castings during extremely cold weather, as they are then easily broken.

58. Location.—The location of an electrical machine cannot always be selected with a view to the best results in operation. The ideal location is clean, dry, well ventilated, easily accessible, and in plain sight. A machine should not be placed where it will be exposed to moisture; provision should be made for protection against drippings from steam or water pipes, or from the roof or wall of a tunnel or a mine. The atmosphere surrounding a machine should not be so warm

that the maximum temperature of the machine, while operating, will exceed the limit for normal running set by the manufacturers. Freedom of the atmosphere from acid fumes is essential.

59. Foundations.—Solid masonry foundations are best for electrical machines, but timber is often used for supporting machines of the smaller sizes. In any case, the foundation should be solid enough to prevent vibration. If it is desirable to insulate a machine frame from the ground, the slide rails or bedplate must be bolted to dry timbers, which are, in turn, firmly fastened to the masonry foundation. The timbers should be treated with some kind of moisture-repelling compound, and they should be countersunk where they receive the bolts that hold the machine bed. The heads of these bolts should be covered with insulating compound. The wood or iron uprights or stringers for mounting motors on ceilings or walls should be heavy and rigidly anchored to prevent vibration.

60. Erection.—Before a machine is firmly fastened to its foundation, the driving and driven shafts must be lined up. The pulleys of a belt drive must be in line, so that the belt will run true. The gears of a gear drive must mesh properly. Two shafts of a direct drive must be in line before the coupling is made. The alinement of pulleys can sometimes be tested by installing the belt temporarily and turning the pulleys by hand; if the alinement is poor, the belt will tend to run off.

Motors in industrial service are frequently mounted on a wall or a ceiling. If such mounting is intended, the manufacturers should be so informed when the order is placed. Some types of motors are provided with bearing brackets, or housings, that can be turned through an angle of 90° for wall mounting and through 180° for ceiling mounting. Sometimes the motor is fastened to its bedplate or its slide rails, as the case may be, before it is hoisted into position; in other cases, the slide rails are mounted in place before the motor is hoisted to its position on wall or ceiling; the method followed depends on the conditions.

Vertical motors must be mounted so that the shaft does not incline from the vertical by an angle greater than the limit set

by the manufacturers. Also, especial care must be taken that the driven shaft is properly alined with the motor shaft. Vertical motors should be very securely bolted to their foundations.

61. Removal of Moisture.—The windings of electrical machines must be dry before full voltage is applied. Machines that have been stored in unheated buildings or have been long in transit should have their windings thoroughly dried before they are put into service.

A machine can be conveniently dried by sending through its windings a current large enough to raise the temperature to about 70° C., but not over 85° C. The temperature should be raised gradually through several hours, the time depending on the size of the machine, and should be kept as nearly uniform as possible throughout the windings. At no time during the drying process should the temperature of the windings be allowed to drop to that of the surrounding air, because the moisture would then condense on the coils. A generator can be dried by its own current, the armature circuit being short-circuited beyond the ammeters and the field excitation being reduced. Field-exciting current from a separate source is preferable. Both the field and armature voltage should at first be kept low, because damp insulation is easily broken down. Some means must be provided for controlling the current, and the temperature of the machine should be watched closely, in order to prevent the interior of any winding from becoming too hot.

Small motors can be dried in ovens. If large machines must be dried by external heat, sheet-iron compartments can be built around them and the interiors heated by charcoal stoves or steam pipes; the latter must be free from leaks. The drying of electrical machinery by any process is very slow. It may take several days to dry a large machine.

BEARINGS

62. When first starting a machine, the bearings should be watched carefully to see that they are receiving proper lubrication. If possible, a new motor should be run for 1 or 2 hours

on light load to make sure that the bearings will work without undue heating.

Most bearing troubles are due to insufficient lubrication, caused by poor lubricant, lack of lubricant, dirty lubricant, failure of oil rings to revolve, clogged oil grooves, or poor grade of waste in waste-packed bearings. Oil that is too thin will not stick to the rings or chains of self-oiling bearings in sufficient quantity to be drawn up on to the shaft, and the bearing will heat due to lack of oil. In large bearings, where the distance that the oil must be lifted by ring or chain is considerable, the oil must be thicker than that used for small bearings. Sometimes oil rings, especially those of small bearings, do not revolve properly; this fault, though rare, should be remedied at once.

63. The first symptom of poor lubrication is heating of the bearing. A motor or generator bearing is usually safe if it operates at a constant temperature below the boiling point of water, but a rapid rise of temperature toward this limit is indicative of danger. An overheated bearing will be hot to the touch and will give off the odor, and perhaps the smoke, of burning oil.

Other causes of heated bearings are poor bearing surfaces, which may be caused by careless handling or by dirt in the lubricant, journal cap too tight, bent shaft, unbalanced rotating parts, bearing out of line, or excessive belt tension.

When an overheated bearing is observed, it should be given an abundant supply of fresh clean lubricant. If this treatment does not afford relief in a reasonable time, part or all of the load should be removed from the machine, which should be kept rotating slowly until the bearing cools; otherwise, the bearing will freeze, or set. When the bearing cools sufficiently, the machine can be stopped and a search made for the trouble. An inexperienced person should not attempt to repair bearings.

ROUTINE

64. The proper maintenance of electrical machinery requires that it be given regular attention to keep it clean and free from moisture, grit, and acid fumes. The operator

should at frequent and regular intervals, make careful inspections of all the apparatus, to note condition of contacts, wear, heating, and general conditions. To be on the alert to prevent trouble, systematic tests should be made to determine the condition of the electric circuits. The insulation resistance tests, described later, should be applied to armature and field windings, machine leads, etc. at frequent intervals.

In the event of any operating trouble or defect in performance, it is important to restore normal conditions as soon as possible. To do this, it is necessary to proceed systematically. Certain symptoms point to certain causes of trouble, and a thorough familiarity with both symptoms and causes is essential; haphazard guesswork may only complicate the trouble.

TROUBLES OF DIRECT-CURRENT MACHINES

POOR COMMUTATION

65. List of Causes.—Under *unsatisfactory performance* of direct-current machines may be included *poor commutation*, *excessive heating of electrical parts*, and *noisy operation.*

Poor commutation may result from overload, improper position (lag or lead) of brushes, hard or high-resistance brushes, rough commutator bars, high mica on the commutator, grounds, short circuits, or open circuits in the armature, high-resistance connections between the armature coils and the commutator, poor brush contact, inaccurate brush spacing, uneven air gap, or weak magnetic field.

66. Overload.—The symptom of overloading is general overheating of the armature and commutator accompanied by sparking, which can be reduced, but not stopped, by properly advancing the brush position. Overloading may also be recognized by comparing the ammeter reading with the nameplate rating of the machine.

67. Wrong Position of Brushes.—For satisfactory performance, the brushes of a direct-current machine must be at

the neutral points of commutation. On most standard machines without commutating, or regulating, poles, the no-load neutral points are in line with the centers of the poles, but the points change positions as the load varies. On generators, especially those that have large armature reaction, the brushes must be set forwards in the direction of rotation as the load increases; on motors, the brushes are set backwards. The amount of change must be determined by experiment for each machine. If the load on the machine is of a more or less fluctuating nature and attention cannot be given to the brush position, the brushes should be left in the position that gives the best average commutation for all loads at normal voltage.

68. Hard Brushes.—Brushes that are too hard or have too high a specific resistance may be unable to carry the current at the contact surface. Some generators require brushes that are harder and of higher resistance than can be used satisfactorily with others. In such cases, some experimenting is usually necessary to determine the proper kind of brushes to use. Brushes should not be changed, however, until it is certain that the cause of faulty commutation is not elsewhere.

69. Poor Commutator Surface.—Eccentricity of the commutator, high bars, low bars, flats, and high mica are all defects that necessitate resurfacing. Eccentricity may be detected by a regular rise and fall of the brushes in their holders, the frequency corresponding to the speed. The commutator should be put into a lathe and turned concentric to the shaft center, or, if preferable, the lathe tool may be carried on a portable holder mounted on the generator frame and the commutator turned in place.

High bars, if not too high, may sometimes be cut down by using carborundum. Sandpaper, or carborundum paper is best for cutting down projecting mica. Emery paper should not be used for this purpose. Low bars and flats are best treated by turning down the commutator with a tool.

70. Armature Defects.—Short circuits, grounds, reversed coils, open circuits, and high-resistance contacts in armatures cause firing, or sparking. If the commutator shows burning

or blackening on certain bars and inspection shows no high or low bars or flats some one of the foregoing troubles should be looked for. Short-circuited armature coils will be indicated by their excessive overheating. Open-circuited coils will not overheat, but will cause severe firing at the commutator bars, as will also high resistance in a coil or at the connection between the coil and the commutator. The commutator bar will usually be found to be burned more on one edge than on the other. The most probable place for the high resistance to occur is at the end joints or in the commutator connection.

71. Poor Brush Contact.—If the curvature of the brush does not properly fit that of the commutator, the effective brush surface is reduced, causing on the active surface a high current density accompanied by overheating and firing. This condition may be found by inspection. The brushes should be resurfaced with a strip of sandpaper drawn back and forth under the brush while in place. In sandpapering brushes, care must be taken to hold the smooth side of the sandpaper down on the surface of the commutator on both sides of the brush. If this is not done, one or both edges of the brush will be rounded off, and it will have contact only at the middle.

72. Inaccurate Spacing of Brushes.—If the brush-holder studs are not properly spaced around the commutator, when the brushes on one stud are set for a non-sparking position those on some other stud will spark because they are not in the neutral commutating plane. The remedy is to set the brushes in the positions, found by experiment, where the largest number of rows are not sparking and to mark the places. Having done this, the brushes are shifted forwards or back, as may be required, to positions where no sparking is obtained on other rows, thus experimenting to find how much it is necessary to move each row forwards or back to secure sparkless commutation. The generator should then be shut down and the brush-holder studs respaced accordingly.

Another method in considerable use for checking the spacing of brushes is to stop the machine and wrap a strip of paper close around the commutator under the brushes and to mark the

paper at the front edge of a brush in each stud. If these marks are not equidistant the brush-holder studs should be respaced.

73. Unequal Air Gaps.—Unequal air gaps between pole faces and armature will cause poor commutation, producing an effect similar to unequal brush spacing. The air gaps can be measured by a long tapering wedge, which is to be inserted into the gaps in a direction parallel to the armature slots. If the air gaps are found to be unequal, they should be corrected by recentering the armature among the field poles. On some machines, the bearing housings are specially arranged for centering the armature; on others, the bearings must be relined.

74. Weak Field.—As a cause of poor commutation a weak field is usually quickly recognized, as it also results in low voltage in a generator and high speed in a motor. If, however, the sparking is confined to one or two rows of brushes, the trouble may be caused by a local weak field due to a high reluctance in the magnetic circuit caused by the pole piece not being tightly secured to the field yoke.

EXCESSIVE HEATING

75. List of Causes.—Excessive heating, another form of poor performance of electrical machinery, may result from errors in design or construction, defective condition of the apparatus, or unfavorable conditions of operation.

76. Errors in Design or Construction.—Electrical machinery is usually subjected to severe test by the manufacturer so that it is very infrequent that defective apparatus is sold. Errors in design or construction include use of the wrong kind of steel for magnetic cores, copper conductors too small or with too low a specific resistance and faulty workmanship.

77. Defective Condition of Apparatus.—Excessive heating of armatures may be caused by poor insulation resulting either from dampness or from carbonization of the insulating fabric by previous overheating due to overloads. A test for low insulating resistance may be made with a high resistance voltmeter, as described later. There will usually be little

difficulty in determining whether or not low insulation results from dampness, as in this case the armature will steam slightly after being shut down. If due to carbonization of the insulating fabric, the insulation will be brittle and weak instead of tough and strong.

Excessive temperature rise in a magnetic core of an armature or a transformer may be a result of severe overheating due to an overload at some previous time. In such cases, the remedy is to rebuild or to replace the core. If large eddy currents are generated in the core, they may be due to the destruction of the coating of insulating japan on the laminations. If this is the case, it will be sufficient to disassemble the core and rejapan the laminations, after which they may be restacked and the winding replaced. This is a very expensive process, and can usually be done only by the manufacturers, or by repair men equipped for such work. Short-circuited armature coils may cause severe local heating which, if not stopped in time, will cause the coils to be burned out.

78. Unfavorable Operating Conditions.—The most common unfavorable condition causing overheating is overload. If it is not possible to reduce the load, every effort should be made to improve the surrounding conditions and to remove as much of the heat as possible by better ventilation. Doors and windows should be open to establish a good circulation of air, and if a fan is available, even of the ordinary desk variety, cool air should be blown on the overheated part.

Unfavorable surrounding conditions include closed doors or windows, close proximity of other heavily loaded machines, uncovered steam pipes, radiation from steam engines, and poor circulation of air. The operator should be on the alert for conditions of this nature and do whatever is possible to remove them.

NOISY OPERATION

79. Noisy operation may be caused by features of design and manufacture, such as high magnetic densities, form and number of armature teeth, etc., or it may be due to mechanical

defects that require attention. Imperfections of design are beyond remedy by the operator.

Brushes loose in their holders or working on a rough commutator are common sources of noise; they should be readjusted or the commutator resurfaced. Armature rubbing against field poles, rotating fields touching armature cores, and induction-motor rotors rubbing against their stators are also mechanical defects indicated by noise. In most of such cases, the noises are barely noticeable at first, as the rubbing is generally slight in the beginning. As it is important that they be found as quickly as possible, the operator should carefully investigate the cause of every unusual sound.

LOW VOLTAGE OF GENERATOR

80. List of Causes.—The service of a generator is unsatisfactory when its voltage is too low. The causes of low voltage are overload, low speed, improper setting of brushes, armature defects, and weak magnetic field. Overloading and wrong position of brushes are recognized by the symptoms given in Arts. **66** and **67**, respectively.

81. Armature Defects.—Armature defects, such as open-circuited, or reversed, coils, lower the generator voltage by reducing the effective number of conductors cutting the magnetic field. Such defects are easily recognized by the kind of sparking on the commutator. Sparking caused by improper brush position or overload is continuous; that due to armature defects is either confined to the commutator bars connected to the affected coils or, if continuous, is more severe on those bars.

82. Low Speed.—Low speed can be detected by means of a tachometer, or speed counter. If the generator is driven by a belt, the speed of the driving pulley and also that of the generator should be taken, in order to determine whether or not there is any slip of the belt. In most cases, belt slip can be recognized by a sharp screeching sound, which may be continuous or intermittent. In some cases, belt slipping is stopped by so moving the generator as to tighten the belt, but as this

increases the tendency to heat the bearings, it is not always the best procedure. If possible, the belt friction on the pulleys should be increased; and it sometimes occurs that this friction is reduced by oil getting on the working surface.

83. Weak Magnetic Field.—Weak magnetic field may be due to improper position of the rheostat contact-arm, causing too much resistance to be included in the field circuit; and it may be caused by a poor magnetic contact causing high reluctance in the magnetic circuit. In order to test the field circuit, turn the rheostat arm to the position for strong field excitation, that is, so as to cut the rheostat resistance out of circuit, and by means of a portable voltmeter measure the fall of potential across the entire field winding, making connections at the field-terminal lugs on the machine frame. If the potential drop across the field winding is less than the machine voltage indicated by the switchboard voltmeter, test each part of the field leads separately in order to locate the defect. If the potential drop in the winding is equal to the generated voltage, test each coil separately, taking care to include in each case the connection to the adjacent coil. If the fall of potential across any coil is found to be very much higher than it is on the others, the high resistance is between the points over which the large pressure drop occurs. The connection should be carefully examined, as it will be much more probable that the high resistance is in one of the connections between coils than inside the coil itself.

FAILURE OF MOTOR TO OPERATE

84. Mechanical Troubles.—The mechanical troubles that may cause a motor to stop or fail to start are severe overload, bent shaft, tight bearings, contact between armature and field poles, brush holders jammed, or excessive friction due to any cause.

A motor of small or moderate size that can be disconnected from its load can be examined for mechanical trouble by turning it by hand. If it turns harder than it should, mechanical trouble is indicated. If resistance to turning is greater at one

point than at others, it may be caused by a bent shaft or rubbing contact between armature and field or between rotor and stator. If the resistance to turning is uniform, or if the rotating parts cannot be turned at all, the bearings may be tight owing to the bearing cap having been screwed down too firmly or to seizing, or freezing, caused by overheating of the Babbitt, due to lack of oil.

Severe overload may cause the fuse in the supply circuit to blow and thus shut down the motor, or, if the load is heavy enough, may prevent the motor from starting. The remedy is, of course, to reduce the load to within proper limits.

85. Electrical Troubles.—The more common electrical troubles that cause failure of operation of a motor are open circuit in the supply, open-field circuit, and wrong connections.

An open circuit in the supply may be caused by a melted fuse, or by a broken wire or connection; the brushes may not be in contact with the commutator; or the current may be shut off at the generating station or at a break in the line.

86. If the field circuit is open, the motor will not start; and if very much of the starting resistance is cut out of circuit, the motor fuse will blow. If from any cause the field circuit is opened while the motor is in operation, the armature speed will increase and the current will become very great; the armature will probably be destroyed if the fuse does not blow. If the motor is under heavy load, the mechanical drag will prevent a rapid acceleration, a heavy current will result, and the fuse will blow or the circuit-breaker will open. A break in the field circuit is indicated by the failure of any pole piece to attract a small piece of soft iron when the field terminals are connected to the source of supply.

87. A break in a field circuit will usually be found, by inspection, to be in one of the leads or connections. If inspection fails to discover the break, the field coils should be tested with a voltmeter, as follows: Connect the field terminals to the source of supply, leaving the armature circuit open. Connect one terminal of the voltmeter to one of the field terminals, making

sure that the polarity is correct. To the other terminal of the instrument connect an insulated wire bared for a short distance from the free end, so as to make a contact point. Touch this point successively to the junctions between the field coils. When the voltmeter shows a deflection, the last coil included by the voltmeter connections is the defective one. The voltmeter must have a range at least equal to the full voltage of the supply.

An open-circuited field coil can also be located by the following method: Connect the field terminals to the source of supply, leaving the armature circuit open, as before. Short-circuit each field coil in succession, each time testing the field poles for magnetism with a small piece of soft iron. When the defective coil has been short-circuited, the field poles will strongly attract the iron. In this case the short circuit should be removed in a way to avoid severe inductive effect.

88. The foregoing has reference to a shunt-field circuit; a break in the conductors or connections of a series-field winding is equivalent to a break in the supply circuit.

89. Wrong connections on motors are uncommon, but among those to be looked for are: Motor armature in series with retaining magnetic coil of starting box; shunt field in series with armature; shunt field connected on wrong side of starting resistance; wrong terminal of the motor connected to the starting box; and part of the field coils reversed.

If the armature is in series with the coil of the retaining magnet, an attempt to start the motor will result in burning out the coil. This error will result from interchanging the field and armature leads at the connection to the starting box.

If the shunt field of a motor is connected in series with the armature, the current from the latter will be so limited as to prevent the motor from reaching any considerable speed.

If the shunt field is connected on the wrong side of the starting resistance, the motor will be weakly excited when starting current is applied and may start badly or not at all. If it starts, the field will be strengthened as starting resistance is cut out and the motor will run slower than normal.

If the armature connection of the starting box is made to the motor terminal to which the shunt field is connected, the fields will be practically unexcited, and the motor may not start, or, if it does, will not speed up, but the fuse will blow or the circuit-breaker will open.

If a part of the field coils are reversed, the error may be found by exciting the fields and using a pocket compass, holding it near the pole pieces in such position as to indicate the polarity of the magnets. If a pocket compass is not at hand, a piece of soft iron bar or a nail may be held so as to bridge across between two adjacent pole pieces. If the bar of iron or steel is held firmly to both pole pieces the poles are of opposite polarity; if it is repelled from one they are alike.

FAILURE OF GENERATOR TO OPERATE

90. A direct-current generator may fail to generate because of wrong connections, open-field circuit, too weak residual magnetism, severe overload, reversed polarity, or poor brush contact.

Wrong connections include such errors as connecting shunt field in series with armature, or reversing part of the field coils. An open circuit in the field circuit will result in no excitation and consequently no generation.

A shunt generator will not build up its voltage if started under a heavy load. It builds up its voltage best on open circuit. Also, in operation, it drops its voltage if a certain critical load is exceeded.

If a generator fails to excite itself, the operator should examine all connections, try a temporarily increased pressure on the brushes, examine the field rheostat for a burn out or a broken coil, test the field coils for open circuit, and check up the position of the brushes. If nothing wrong is found with the connections or the windings, it may be necessary to excite the field from an outside source of energy in order to restore the residual magnetism.

91. If the residual magnetism is too weak or is completely destroyed, the poles will not attract pieces of soft iron held in such position as to bridge across two adjacent poles.

If the machine is compound wound and another machine is in operation, close the equalizer connections of both generators and close to the bus the armature switch of the same polarity as the equalizer connection of the unexcited generator. A part of the output of the running machine will then pass through the series-winding of the unit that will not generate. If the machine is then run at full speed, the generator will pick up.

If the machine is shunt wound and current from another machine or a storage battery is available, pass current from the running machine in proper direction through the fields but not through the armature. The procedure is as follows: Open the armature circuit by disconnecting one terminal of the armature leads between the shunt field tap and the armature; close the main armature switches to the busses to which the running machine or the storage battery is connected; first strengthen and then weaken the field excitation by means of the field rheostat; open the armature switches, taking care to open the first one slowly, drawing out a long arc, to avoid a high inductive electromotive force in the field winding; reconnect the armature terminal and start in the usual way.

92. If no other generator or storage battery is available, disconnect one terminal of the shunt-field circuit and connect it to one terminal of a few primary cells in series. Connect the other terminal of the battery to the remaining shunt-field terminal. Use cells with large current capacity and take care to connect the positive terminal of the battery to the positive end of the field circuit. Connect a portable voltmeter between the disconnected terminal of the shunt-field winding and the binding post from which it was disconnected. The instrument will then indicate the voltage of the batteries while exciting the fields. Cut out of circuit all resistance in the field rheostat, and start the machine. When the voltage of the generator is equal to that of the batteries, which will be indicated by the voltmeter reading being reduced to zero, reconnect the shunt-field terminal and immediately disconnect the battery. If the voltmeter reading cannot be reduced to zero,

it is an indication that more exciting current is required; either more cells should be connected in series to secure higher potential or additional cells should be connected in parallel with those already in circuit, in order to obtain a larger current capacity. High-voltage machines, 500 volts, require more cells than do those of lower potential.

93. Reversed polarity of a generator will be indicated by reversed readings of the main voltmeter. It may be corrected by either of the first two methods (Art. **91**) given for exciting a machine that has lost its residual magnetism. If no other generator or storage battery is available, the third method (Art. **92**) may be used, but in this case about twice as many cells will be needed as for mere excitation.

TROUBLES OF ALTERNATING-CURRENT MACHINES

INDUCTION-MOTOR TROUBLES

94. Alternating-current machines are free from troubles due to poor commutation, which is the chief cause of unsatisfactory operation of direct-current machines. Beyond routine inspection and cleaning, alternating-current machines require very little care. Most of the troubles of alternating-current motors are due to faults in the external, or supply, circuit. The effects of variations in the energy supply can be learned from a study of the performance, or operation, characteristics.

95. Shut-Down of Motor.—A shut-down of an induction motor may be caused by an overload or by any condition producing excessive friction. Especial attention should be given to inspection of the air gap of an induction motor that has been in operation for a considerable time. The air gaps of induction motors are made as small as is consistent with proper clearance; consequently, a comparatively small wear on the bearings may let the rotor rub against the stator, which

will eventually cause enough friction to shut down the machine, and, at the same time, may cause considerable damage to it.

A break in one leg of the supply circuit will cause a shut-down unless the motor is lightly loaded. Also, a low supply voltage may so reduce the torque that the motor is no longer able to carry its load.

96. Failure of Motor to Start.—The failure of an induction motor to start may be due to any of the troubles that cause a shut-down. If the starting voltage is too low, the motor will not start; if too high, it will start too rapidly and will take excessive current. Also, the torque will be greatly reduced when the switch is in the running position. An open circuit in the autostarter will, of course, prevent the motor from starting.

97. Winding Faults.—Winding faults in induction motors are very rare, but sometimes they exist in new motors, having escaped the notice of the factory inspectors. These faults may be looked for if examination fails to reveal any of the troubles previously given.

With one leg of a phase-wound rotor open, the motor pulls in at about half speed and continues to run at the same rate. The primary currents will be unbalanced, and the pull-out torque of the motor will be reduced. A reversed primary coil or a short-circuited primary coil will cause unbalanced primary currents and overheating. If one phase of the field is open-circuited, the motor will refuse to start.

Squirrel-cage rotors with soldered bars sometimes cause trouble, due to poor contacts at some of the joints. When some of the joints are bad, the motor will take unbalanced currents and may not come up to speed.

SYNCHRONOUS-MOTOR TROUBLES

98. The failure of a synchronous motor to start may be due to faulty connections in the motor leads or in the starting compensator. Inspection should be made for poor contacts or open circuits. An open circuit or a short circuit in one phase will prevent starting. Ammeters in the circuit will indicate

whether the trouble is an open circuit or a short circuit, giving zero reading for the former and abnormal reading for the latter.

Too much load or excessive friction will prevent a start. The ordinary synchronous motor will not start with more than one-third of its full-load torque. The field should be left unexcited until the motor reaches nearly synchronous speed; it will not start with excited fields.

99. Poor Torque.—If poor torque is developed by a synchronous motor, the trouble will generally be found in the field circuit. A glance at the exciter voltmeter or pilot lamp will tell whether the exciter is generating its proper voltage. An open circuit in the motor-field winding or rheostat will cause the motor armature to take excessive current; the motor will stop or develop excessive heat. A short-circuited or reversed field coil will manifest itself by causing the motor to require more than the normal field current for a given load.

100. Overheating.—Overheating of a synchronous motor is frequently due to an attempt to make the motor carry its rated load and at the same time to adjust the field to improve the power factor on the line. A short circuit in an armature coil usually burns out the coil completely.

DANGERS OF PHYSICAL INJURY

DANGERS FROM MECHANICAL SOURCES

101. The operator should be especially careful to avoid contact with moving belts, gears, rotating armatures, or fields, flywheels, etc. When working in the neighborhood of rotating machinery, he should avoid proximity to live circuits, or to static discharge from belts, either of which may cause an involuntary movement that may bring about a dangerous contact with the belt or with gears, or other rotating parts.

Bursting of rotating parts may cause pieces to be thrown about with great force. Such bursting may, in some cases, be caused by errors in operation, as, for example, the opening

of the field circuit of a direct-current motor while the armature is still connected, or the opening of the field circuit of a rotary converter while disconnected from the alternating-current supply and still connected to a source of direct current. Under these conditions the acceleration is generally very rapid, and only a few seconds may be required for the armatures to reach dangerous speeds.

DANGER FROM ELECTRICAL SOURCES

102. The extent of danger due to electric causes depends somewhat on the character of the apparatus, being greater when the voltage is high and when the safeguards are inadequate. It is not practicable to name any particular voltage as a safety limit, as a voltage that might be harmless to one individual might be fatal to another. Again, a pressure that would be harmless if applied across the hand, might cause instant death if so applied that the current would flow through the heart or the brain. In addition to the danger of injury due to electric shock is that due to electric burns, of which there are two kinds, flesh and contact burns. For these reasons two safe rules are: Never allow any part of the body to become a part of an electric circuit; and never expose any part of the body to even close proximity to an electrical arc.

103. In order to avoid accidentally causing a part of the body to become a part of a circuit, the operator should be careful, when obliged to touch live parts, to stand in such a manner that he touches them with only one part of the body. If any portion of the machine circuit is grounded, the ground is also a live part, and contact with it when handling the machine, is to be avoided. The last statement applies to street-railway systems having one side grounded, to alternators having one conductor or a neutral connection grounded, to grounded three-wire systems, or to any similar arrangement. Thus is indicated the advisability of using an insulated platform, stool, rubber mat, rubber shoes, or rubber gloves.

A dry wooden floor is ordinarily good insulation for potentials up to 250 volts; dry white pine is better than the hardwood.

A $\frac{1}{4}$-inch to $\frac{1}{2}$-inch pure-rubber mat, if clean and dry, is good protection up to about 1,000 volts. For pressures exceeding 1,000 volts, nothing less safe than a stool with good glass or porcelain insulators should be used, and the safer practice is not to touch live parts carrying such voltages.

104. In order to avoid the possibility of current through some part of the body, it is advisable, whenever live circuits must be handled, to do as much as possible of the work with one hand. The other hand should be kept on the side of the body away from live parts, and care should be taken that the knees do not touch the machine frame while work is being done with the hands.

High-tension three-phase systems are now generally grounded at their neutral points, and therefore a person standing in electric contact with the ground and touching any one of the phase conductors would complete a circuit to the earth. When the voltage is very high, care must be taken not to come into even close proximity to the conductors on account of the possibility of a jump to the body. Such a jump is more liable to occur from a point or sharp angle on the conductor than from a flat or round surface.

No work on high-tension equipment should be done without permission from the person in charge of such matters, as it is nearly always necessary to disconnect the equipment from the system. The cleaning and inspection of high-tension equipment is usually done at regular intervals under the supervision of the chief operator, who takes the necessary precautions to render the work safe.

105. Electric burns may result from blowing fuses, accidental short circuits, breaking heavy currents with air-break switches, or causing current to flow through a part of the body. In breaking heavy currents with air-break switches, if the pressure tending to maintain the arc is high, the hands and face should be protected against the effects of the arc. Where there is a back feed, as in the case of a parallel system, this condition is not likely to be serious. When inserting or replacing potential transformer fuses, the operator should stand on a

sufficient insulator and use rubber gloves or a pair of insulating tongs, or both, if possible.

106. The operator should always remember that the source of danger is invisible, that it must be guarded against by continual vigilance, and that, as he becomes proficient in the operation of electrical machinery, there is danger of a growing tendency toward carelessness due to familiarity.

TESTS FOR FAULTS IN ELECTRICAL CIRCUITS

CLASSIFICATION

107. Tests for faults in electric circuits are of two kinds, qualitative and quantitative. *Qualitative tests* are made merely to detect the existence or nature of a fault; accurate measurements are not required. *Quantitative tests* are those requiring more careful use of measuring instruments. In practice, a circuit may be divided into parts, each of which is tested; then the series of qualitative tests combined form a location test. The most common forms of faults in electric circuits are *breaks*, *crosses*, and *grounds*.

QUALITATIVE TESTS

TESTING DEVICES

108. A **magneto-bell**, Fig. 14, is a small, hand-power, alternating-current generator connected to a bell similar to the call bell on a telephone. The armature is driven at high speed by means of gears g and p. The test leads are attached to terminals t and t'.

A magneto-bell is used by applying the test leads to the circuit to be tested and turning the crank of the generator. If

the circuit is complete and within the resistance through which the magneto is designed to ring, the bell will ring. The failure of the bell to ring indicates that the circuit between the magneto terminals is open, or of a resistance too great to pass enough current to ring the bell. If the generator turns very hard when the bell rings, the indication is that the resistance of the circuit is low.

A magneto-bell should not be used for an insulation test between the frame and armature of a large machine, between coil and core of a large transformer, between the sheath and the conductors of a long cable, or on any other circuit of considerable electrostatic capacity. Such a circuit may act as a condenser, receiving current enough to cause the bell to ring, and thus indicate a complete conducting circuit between the terminals of the magneto, even though the insulation is practically perfect.

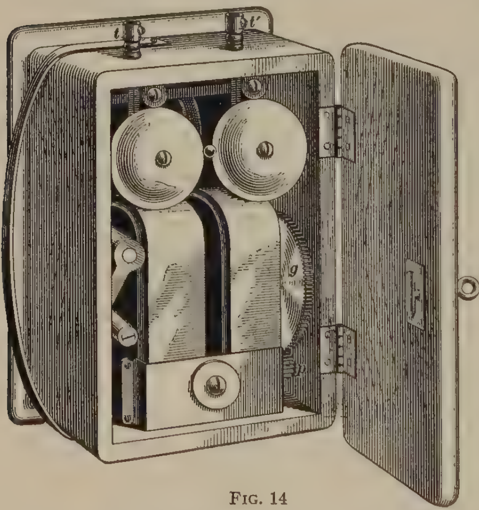


FIG. 14

109. A test-lamp outfit consists simply of a long extension cord terminating at one end in an attachment plug or other device for connecting the outfit to a source of current supply and at the other end to an incandescent-lamp socket or a series of sockets. One of the conductors of the extension cord is cut and the ends thus made are bared for making electric connection to the circuit to be tested. Enough incandescent lamps must be connected in series to burn properly when supplied with the test voltage available.

In using the outfit, the test circuit is connected to the source of current supply and the two free ends of the test leads are

applied to the circuit to be tested. The lighting of the lamp indicates that the circuit is complete. If alternating current is supplied to the test circuit, the same limitations apply to the use of the lamp outfit as to the use of the magneto-bell.

110. Testing With Telephone Receiver.—A telephone receiver connected in series with one or two primary cells, dry cells, if in good condition, are preferable, serves as a convenient testing outfit. The terminals of the series combination are applied to the circuit to be tested. The telephone receiver is held to the ear and the contact of one of the test terminals with the circuit under test is made and broken repeatedly. If the circuit under test is complete, each make or break of the contact will cause a click in the telephone receiver; if the circuit is open, no click will be heard. The device is subject to the same limitations as the magneto-bell.

111. Testing With Voltmeter.—A voltmeter connected in series with the circuit to be tested and a source of electromotive force can be used for qualitative tests. The range of the voltmeter should be at least great enough to accommodate the total voltage impressed on the circuit. When properly connected, a deflection of the voltmeter needle indicates a complete circuit; no deflection shows an open circuit; a relatively small deflection indicates a high-resistance circuit. A direct-current voltmeter can be used in a wide field of testing work.

112. Detector Galvanometer.—A detector galvanometer is an inexpensive portable instrument that is designed for testing the condition of circuits. The instrument is connected in series with a battery, and the terminals of the series combination are applied to the circuit to be tested. If the needle remains at rest under these conditions, either no circuit or one of very high resistance exists. A deflection of the needle indicates a circuit, the amplitude of the deflection being, roughly, inversely proportional to the resistance. The galvanometer is not subject to the limitations encountered in the use of the magneto-bell, the telephone receiver, or a voltmeter on alternating current.

CONTINUITY TEST

113. **A continuity test** is made to determine whether or not there is a break in a conductor. The terminals of the test circuit are applied to the extremities of the conductor and the indications of the testing device are observed. In some cases, it may be necessary, in order to reach the remote end of a conductor under test, to use as part of the test circuit another conductor known to be continuous.

In order to test a transmission line for continuity, the line conductors must be connected together at the distant end. The test terminals are then applied to the station end of the line. If the transmission line is long, only direct current should be used for testing for continuity; in tests on short lines, a magneto-bell is convenient. The term *transmission line*, as used in this connection, includes underground cables.

114. If the line tested is found to be open-circuited, the faulty section is located by applying the continuity test to different parts of the circuit until the break is located. For example, assume that a test on an overhead line shows it to be open-circuited. The tester proceeds along the line, applying the test terminals at intervals. As soon as the tester has passed the break, the testing device will give indications of a closed circuit. The tester then knows that the fault is in the part of the line between the places where the last two tests were made and he proceeds to locate the break by inspection.

Sometimes the procedure is varied somewhat. The tester goes first to a point about midway between the ends of the line and applies the test terminals. If the test indicates an open circuit, he knows that the fault is in the half of the line beyond; if the test indicates continuity, the break is in the other half. The tester thus at once eliminates one-half the line as a possible container of the fault. A few more tests on the faulty half of the line will probably locate the break within reasonable limits.

TEST FOR CROSSES AND GROUNDS

115. A test for a cross or ground is made to determine whether or not a conducting path exists between two objects, two circuits, or two parts of circuits that should be insulated from each other. The test terminals are applied to the two objects or circuits, and the existence of the fault will be indicated by the action of the testing device. If the test lamp, when used, burns very dimly, the indication is that the cross or ground is of small current-carrying capacity and moderately high resistance.

In general, a test for a leak should be made with a device, such as a magneto, voltmeter, galvanometer, or telephone receiver, requiring only a small current to give an indication. In testing for a short circuit, a test lamp is generally more satisfactory.

DIFFERENTIAL TEST

116. It is sometimes necessary to locate, by a test at the station, a ground occurring several miles away on a series-arc-lamp circuit. For this purpose, a crude form of Wheatstone bridge is used. A series of incandescent lamps is connected across the terminals of the arc-lamp circuit, as shown, roughly, in Fig. 15. Generally, the arc lamps require about 50 volts each, and incandescent lamps rated at about 50 volts are therefore preferable; 110-volt lamps can be used, however, if 50-volt lamps are not available. In any case, the number of incandescent lamps in series should be equal to the number of arc lamps in circuit.

The electromotive force of the generator is consumed in sending currents through the parallel circuits of arc lamps and test lamps. From the positive terminal of the generator to the ground *a*, Fig. 15, on the arc circuit, there is a drop in potential of approximately 50 volts per lamp, or, in this case, $6 \times 50 = 300$ volts. If the movable arm *b* of the testing device is moved from contact *c* toward contact *d*, a point will be reached where the potential drop in the test-lamp circuit is the same as that between the positive terminal of the arc

circuit and the ground. There will then be no current through the detector galvanometer *e* and its needle will rest at the zero position. On further movement of the arm *b*, the galvanometer indication will be reversed. The number of test lamps between the positive terminal of the circuit and the test point at which the deflection of the galvanometer needle is zero is equal to the number of arc lamps between the positive terminal of the circuit and the ground. In this case, the number is six.

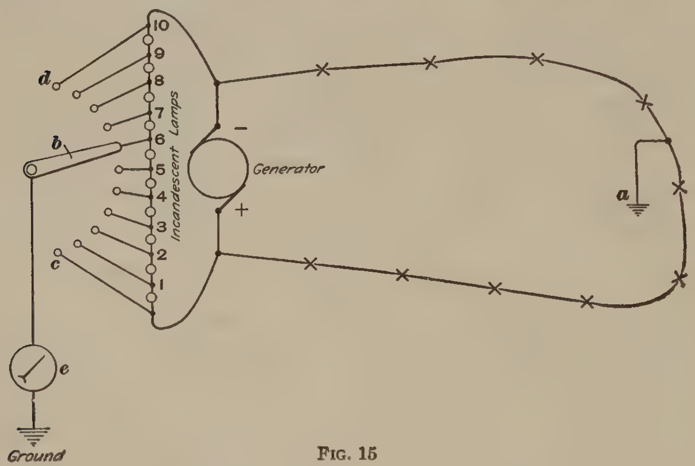


FIG. 15

A voltmeter can be used in place of the galvanometer, but it must be capable of indicating at least half the total voltage of the circuit, and the test must then begin with the arm *b* on the middle contact so that only half the voltage can be applied to the voltmeter. A double-throw voltmeter is preferable; if a single-throw instrument is used, care should be taken not to connect it so as to cause reversed deflection.

TESTS FOR DEFECTS IN DIRECT-CURRENT ARMATURES

117. Faults in direct-current armatures are conveniently located by what is known as the *bar-to-bar test*. Suitable contacts *A* and *B*, Fig. 16, are clamped to opposite sides of the commutator. Current from the mains, or bus-bars, *E* is led

to the commutator through a lamp bank *LB*. A movable contact piece, or *crab*, *C* provided with two spring contacts so spaced as to rest on adjacent bars, is connected to a galvanometer or a low-reading direct-current voltmeter *G*.

For the sake of illustration, it is assumed that in coil *N* there is a short circuit, that the commutator leads of coils *S*, *K*, and *W* have been mixed, as shown, and that there is an open circuit in coil *T*. The test is carried out as follows:

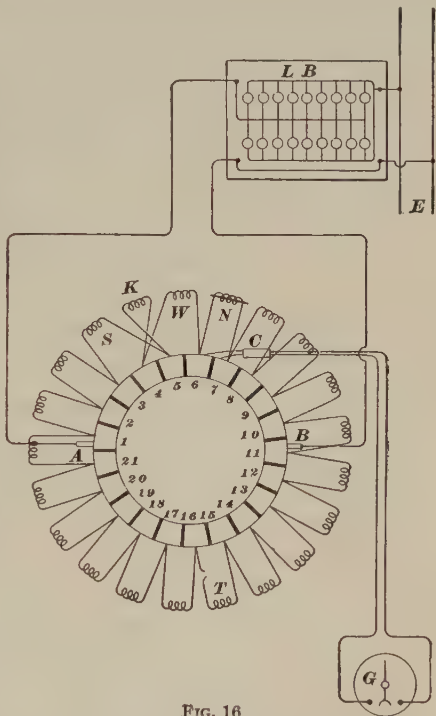


Fig. 16

118. Adjust the lamp bank until the galvanometer gives an easily readable deflection when the crab *C* is in contact with bars connected with what are supposed to be good coils. This serves as a standard deflection, with which to compare other deflections; all but defective coils will give this standard deflection.

When the test contacts rest on bars *3* and *4*, the deflection will be much larger, about double, than the standard deflection, because two coils, instead of one, are connected between these bars. When the contacts rest on bars *4* and *5*, the deflection will be reversed, because the leads are crossed, but will not be greater in amplitude than the standard. Between bars *5* and *6*, a large deflection will be obtained, for the same reason that a large deflection is obtained between bars *3* and *4*. Between bars *6* and *7* little or no deflection will be obtained, owing to the short circuit in coil *N*.

As the contact piece is moved around on the lower side of the commutator, no deflection will be obtained until bars *15* and *16* are bridged. There will then be a violent throw of the galvanometer needle, carrying it beyond the scale. When the contact piece is moved on to bars *16* and *17*, there will again be no deflection, thus locating the break in coil *T*. In order that the other coils connected to the bars in the lower half of the commutator can be tested, bars *15* and *16* must be connected together by a piece of wire.

If any of the coils has poor connections with the commutator bars, the effect will be the same as though the coil had a higher resistance than normal, and the galvanometer deflection will therefore be greater than the standard deflection.

QUANTITATIVE TESTS

MEASUREMENT OF INSULATION RESISTANCE

119. The insulation resistance of a circuit may be conveniently measured by means of a direct-current voltmeter.

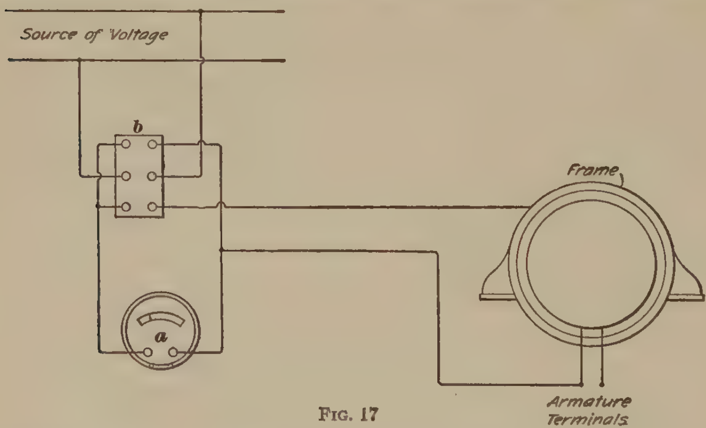


FIG. 17

The instrument should have a known resistance of 90 to 200 ohms per volt of maximum scale reading, and the marks on the scale should be uniformly spaced. As an example of

the method of making the test, the measurement of the insulation resistance of a single-phase alternator is given; the method of applying the test to a transmission-line circuit is described in another Section.

The voltmeter a, Fig. 17, is connected to a double-pole double-throw switch b in such a manner that when the switch is in one position, upper position in this case, the instrument is connected directly across the source of voltage. With the switch in the other position, the voltmeter and the insulation of the machine are in series across the source of voltage. One of the test leads is connected to the frame of the machine; the other, to the windings.

If r = resistance of voltmeter;
e = reading obtained with voltmeter across source;
e_1 = reading with voltmeter in series with insulation;
R = insulation resistance.

Then,
$$R = \frac{r(e - e_1)}{e_1} \qquad (1)$$

The result will be expressed in ohms or megohms according as r is expressed in ohms or megohms. Some voltmeters for use in insulation tests are specially made with a resistance of 1 megohm. The preceding formula then becomes

$$R = \frac{e - e_1}{e_1} \qquad (2)$$

and the result is in megohms.

MURRAY LOOP TEST

120. The Murray loop test uses a Wheatstone bridge arrangement for locating a ground on one conductor of a line, the other conductor of which is continuous and ungrounded. The connections for the test are shown in Fig. 18, in which $a\,b$ is a slide wire, c a galvanometer, d a battery, and e a flexible-cord connection between slide-wire terminals and line. The line wires are connected together at the distant end.

The manipulation consists in moving the contact maker f along the slide wire from point to point, care being taken not

to scrape the wire, until a point is found where a connection can be made without causing a deflection of the galvanometer needle. If the contact maker is moved very slightly to one side of this point, the galvanometer needle should deflect in one direction; if moved to the other side, the deflection should be reversed; thus the condition of a true balance of the bridge is verified.

121. In order to calculate the distance x to the ground, the length of the line must be known. The total length of line conductor in the loop is twice the length of the line, provided, of course, that the line conductors are of equal length, as they are in most parallel systems of distribution.

Let l = total length of line conductor;
x = distance to ground, Fig. 18;
m = distance $b\,f$ at balance;
n = length of slide wire $a\,b$;

$$z=\frac{m}{n}.$$

Then, $$x=z\,l$$

The value of z is the ratio between the length of the shorter arm of the slide wire, at balance, to the total length of the slide

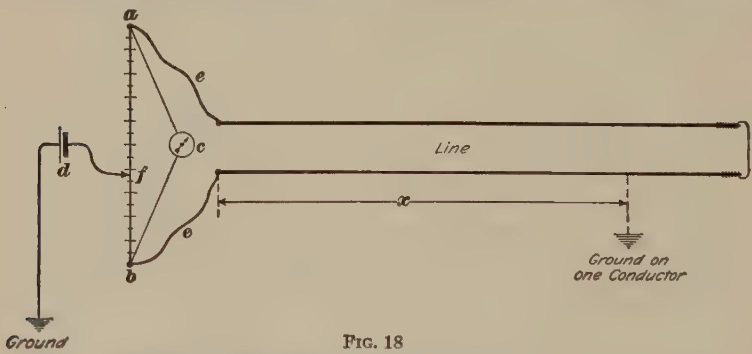


FIG. 18

wire. Generally, the slide-wire scale has a total of 100 or 1,000 divisions, and the value of z can be written as a decimal fraction as soon as the balance point has been found. For example, if the total number of scale divisions in Fig. 18 is 1,000

and a balance is obtained with point $f=375$ divisions from point b, then $z=\frac{375}{1000}=.375$. As used here, the term *number of scale divisions* may include the equivalent, in divisions, of a fixed resistance.

After one balance is obtained, the battery terminals and the slide-wire connections should be reversed and the observations repeated. If the two sets of observations give unlike values of z, their average should be used in the calculations.

122. When applying the Murray loop test, the following considerations must be kept in mind: Connections should be carefully made, so that contact resistance will be inappreciable. If the line conductors are of different sizes, it is necessary to calculate the various lengths in equivalents of one chosen size of wire. The flexible leads e, Fig. 18, are generally so long that their lengths also must be reduced to an equivalent length of line conductor and included in the value of l in the formula of the preceding article.

EXAMPLE.—An underground line contains 20,000 feet, one way, of 211,600-circular-mil, twin-conductor cable and 25,000 feet of 250,000-circular-mil cable. The 211,600-circular-mil cable is at the station end of the line. The two flexible connections e, Fig. 18, are each 10 feet long and equivalent in cross-section to No. 14, B. & S. gauge, wire. The slide wire is 100 units in length, and when the balance is obtained, the contact maker is at a point 27.4 units from the zero end of the wire. How far from the station is the ground?

SOLUTION.—For convenience, all conductors in the line circuit are reduced to equivalent lengths of 250,000-cir.-mil cable. The equivalent length of 20,000 ft. of 211,600-cir.-mil cable is $\frac{20,000\times 250,000}{211,600}=23,629$ ft. The equivalent length of 10 ft. of No. 14 wire, 4,106 cir. mils, is $\frac{10\times 250,000}{4,106}$ $=608$ ft. The length of the line expressed in terms of 250,000-cir.-mil cable is then $608+23,629+25,000=49,237$ ft. As this length is taken one way, the total equivalent length of conductor in the line circuit during the test is $2\times 49,237=98,474$ ft. The value of z is $\frac{27.4}{100}=.274$. The equivalent distance to the ground is therefore $.274\times 98,474=26,981$ ft.

The equivalent distance must be reduced to actual length of line. The first 608 ft. of equivalent length is in the flexible connections, leaving

26,981 − 608 = 26,373 ft. of equivalent length in the line. Of this remainder, 23,629 equivalent feet are of 211,600-cir.-mil cable. The ground is therefore 26,373 − 23,629 = 2,744 ft. beyond the end of the 211,600-cir.-mil cable, or 20,000 + 2,744 = 22,744 ft. from the station. Ans.

123. The Murray loop method, when properly applied, will generally give good results, and the location of the fault as determined by the calculations will be within a short distance of the actual location. In general, the larger the size of the line conductors, the greater will be the liability of error and the greater must be the care exercised in taking the observations. The chief advantage of the method is that an inexpensive slide-wire bridge can be used and accurate resistance units are unnecessary.

VARLEY LOOP TEST

124. The Varley loop is another application of the principle of the Wheatstone bridge. It is more complicated than the Murray loop, but is capable of wider application, though with somewhat less reliable results.

The Varley loop method is especially useful in locating a ground when no good conductor is available as a return. The connections for the unit-resistance type of bridge are shown in Fig. 19 and those for the slide-wire type in Fig. 20. The flexible

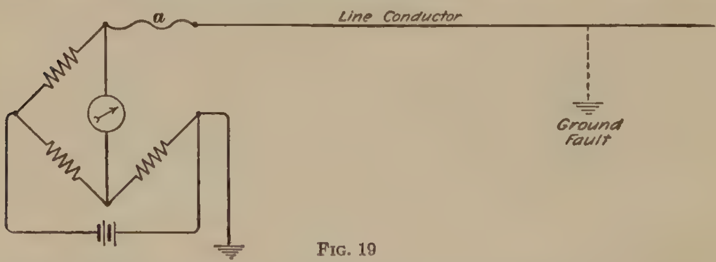


Fig. 19

lead to the line conductor is shown at *a*. In each test in which the slide-wire bridge is used, the resistance *b*, Fig. 20, should have a value such as to cause a balance to be obtained when the contact maker is somewhere near the middle of the bridge wire.

The resistance of the line must be known either from previous measurement or from calculation. If the cross-section

of the line conductors is not the same throughout, the length of the line must be expressed in equivalents of one size of conductor. The resistance of the flexible lead *a* must also be taken into consideration, as in the Murray loop test.

125. With the bridge connected as shown in Figs. 19 or 20, obtain a balance and calculate the resistance, using the ordinary Wheatstone-bridge formula; call the result *n* ohms. Ground the distant end of the line and take a second measurement;

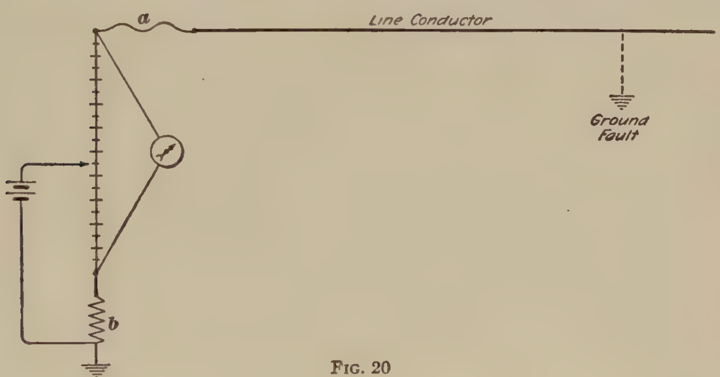


FIG. 20

call the result *p* ohms. Call the normal resistance of the line *m* ohms. Then the resistance from the bridge terminal to the fault is

$$r=p-\sqrt{(n-p)\,(m-p)}$$

From the value *r* subtract the resistance of the lead *a*. The remainder is the resistance of the line conductor from the station to the fault. If the conductors are not all the same size, calculate the resistance of each size and locate the ground as in the example of Art. 122. The result thus found may be unreliable, and, in general, should serve only as a guide to the actual location of the fault.

126. If the fault is a cross to another conductor, the Varley loop test can be used as already explained, one conductor being considered as under test and the other as the ground.